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THE DISTRIBUTION OF ERUPTIVE PROMINENCES ON THE SOLAR DISK[1]

By PHILIP FOX

Spectroheliograms taken with calcium radiation using the H or K line often show especially brilliant points in the flocculi in the neighborhood of spots. These were noticed by Hale and Ellerman in their early work with the Rumford spectroheliograph and even earlier on the Kenwood spectroheliograms. On account of their brilliancy and occasional rapid change of form, and because hydrogen spectroheliograms generally had brilliant points in the same region, they were called eruptions.[2]

While I have been observing with the Rumford spectroheliograph I have given these eruptions careful attention and the evidence seems conclusive that they are the bases of eruptive prominences. Observations of their spectrum made visually and photographically show that the reversals of the H and K lines, indicative of the presence of flocculi, are here very strong and often show distortion; that the $H\epsilon$ line is always reversed and sometimes many of the metallic lines; though none, so far as my observations go, that are not seen in the spectrum of eruptive prominences. Observations on September 12, 1907, will

[1] The essence of this paper was contained in two communications: (1) to Section A of the American Association at the Chicago meeting, January 1908, "The Detection of Eruptive Prominences on the Solar Disk;" (2) to the Astronomical and Astrophysical Society of America at Put-in-Bay, August 1908, "The Distribution of Eruptive Prominences on the Solar Disk."

[2] *Publications of the Yerkes Observatory*, **3**, Part I, 18 and 22.

illustrate. There was on my photographs such a brilliant eruption in the midst of the small spots of the group then just past the central meridian in the southern hemisphere, Greenwich No. 6247 and 6252. Hurried, visual examination in the blue and violet showed a number of lines reversed. Besides H and K there were $H\delta$, $H\epsilon$, $H\zeta$, iron lines at λ 4046 and 4005, strontium at λ 4078, calcium at λ 4227, and aluminum at λ 3961 and 3944—all prominence lines. A photograph of the limited portion of the spectrum admitted to the plate through the opened second slit of the spectroheliograph, about 65 Ångströms in the region of the H and K lines, shows the reversal of the two aluminum lines mentioned above. Young in discussing spot spectra makes the following statement:[1] "At times the spectrum of a spot gives evidence of violent motion in the outlying gases by distortion and displacement of the lines. When the phenomenon occurs, it is more usually at points near the outer edge of the penumbra." He was surely observing the phenomena under discussion here. Again he says: "In a few instances the gaseous eruptions in the neighborhood of a spot are so powerful and brilliant, that with the spectroscope, their forms can be made out on the background of the solar surface in the same way that the prominences are seen at the edge of the sun. In fact, there is probably no difference at all in the phenomena, except that only prominences of most unusual brightness can thus be detected on the solar surface." Deslandres states:

> La zone moyenne (autour de la pénombre) est le siège de mouvements notables, indiqués par l'inclinaison fréquente de la raie K_3 par rapport à la raie K_2, inclinaison qui, parfois, a pu être expliquée par un mouvement tourbillonnaire analogue à celui des cyclones terrestres et de même sens; cette région doit être le siège des protubérances dites éruptives.[2]

A line of evidence other than deductions from observations of the spectrum is opened when we detect these eruptions near the limb. In 1905 I noted that:[3] "In nearly all cases where these eruptions could be traced to the limb the prominence plate revealed a prominence hovering over the (eruptive) flocculus." Since then the instances of detected coincidence have been multiplied. Perhaps the most beauti-

[1] Young, *The Sun* (rev. ed., 1904), p. 135.

[2] *Comptes Rendus*, **141**, 382, 1905.

[3] *Astrophysical Journal*, **21**, 354, 1905.

PLATE XVIII

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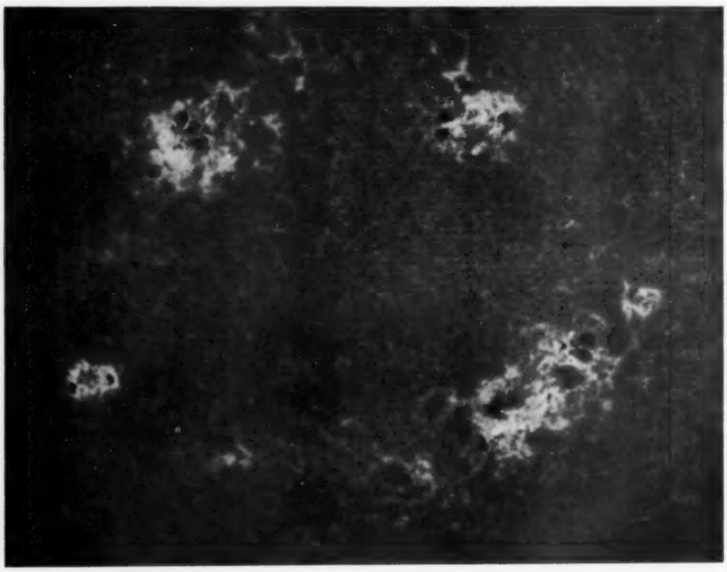
FIG. 1.—COMPOSITE OF CALCIUM PROMINENCE AND DISK PLATES OF AUGUST 14, 1907. TWOFOLD ENLARGEMENT

E  W

S

FIG. 2.—CALCIUM PLATE OF AUGUST 4, 1908, SHOWING ERUPTION PRECEDING THE NEW SPOT. ORIGINAL SIZE

ful illustration found on our photographs is seen on plates obtained August 14, 1907. The flocculi plates showed a brilliant ridge in the cloud of calcium vapor about the group of spots just rounding the east limb of the sun at position angle 132°, Greenwich No. 6236. This was particularly strong on a plate at 3^h 50^m G.M.T. The prominence plate at 4^h 17^m, though badly fogged, showed the associated prominence. A second plate at 5^h 36^m was of better quality. Fig. 1 of Plate XVIII is a composite of the disk exposure at 3^h 50^m and the prominence plate at 5^h 36^m. The prominence bears a strong resemblance to the one observed by Young[1] on October 5, 1871. Other striking illustrations of this coincidence might have been made with plates of September 13, 1907, July 14, 1908, July 25, 1908, July 31, 1908, etc.

The spectroheliograms, then, show the bases of the eruptive prominences and provide a means for studying their distribution on the disk. During the present year at free moments I have been engaged in making a careful examination of all the Rumford spectroheliograms, recording in ledger form all phenomena of interest, noting the location of dark flocculi, eruptions, prominences at the limb, etc. This was undertaken primarily to show the distribution of the eruptive prominences on the disk. Before giving the summary of this feature of the ledger I will refer again to Young's observations and to others by Buss. Young, as quoted above, found the eruptions at the outer edge of the penumbra. Mr. Buss,[2] in summarizing observations made during the past ten years, describes spectroscopic observations of prominences on the disk similar to those of Young. He says: "These paroxysms usually take place behind the leader spot of an active group, in the intervening area between the leader and the chief follower, and must be intimately bound up with the evolutions of spot formation."

My observations are in absolute accord with the above, as this summary from my ledger shows: Spot birth is always accompanied by and generally antedated by an eruption. In the early hours of the life of the spot the eruption may partially or entirely cover the spot and often may precede it, in the direction of solar rotation. An eruption

[1] Young, *The Sun* (rev. ed., 1904), p. 223, Fig. 71.

[2] *Journal of the British Astronomical Society*, **18**, 238 and 240, 1908.

is seldom seen preceding a mature single spot but if present will be following it at the edge of the penumbra, perhaps encroaching somewhat. If the spot is actively growing eruptions are almost certain to be found on the following edge. Eruptions accompany spots in rapid decline, being often seen at the ends of bridges. In complex spots where we often have a large leader, *a*, and a large spot, *b*, at the end of the stream the eruptions follow the preceding spot and precede the following spot. The instances of an eruption preceding the spot *a* or following the spot *b* are comparatively rare. Usually in such a group we find a great number of smaller spots between *a* and *b;* eruptions are usually seen among them.

The distribution of the eruptions about the spots and the similarity of arrangement of calcium and hydrogen eruptions is shown in Figs. 2, 3, and 4 of Plates XVIII and XIX. The exposures for Fig. 3 (calcium, H line) and Fig. 4 (hydrogen, $H\alpha$) were made on August 3, 1908, that for Fig. 2 (calcium H), on August 4. The eruptions between the leading spot and its followers of the southern group are in a well-marked chain. In this Fig. 2 shows considerable changes. More striking, however, is the advent of the new spot. Here, as is often the case, an eruption precedes the leading spot. It persisted in this position until August 6, then disappeared; only the eruption in the usual position between the spots remained. It is well also to say here that the north preceding spot was born on August 1. Mention will again be made of this spot. It and its southern companion were on the western limb on August 10, and both were actively emitting prominences. The following pair were showing similar activity on the limb on August 12 and 13.

It is natural to turn from these observations to a consideration of the relation of eruptions to the spots. I think the evidence of the Rumford spectroheliograms fairly conclusive in showing that the spot has its genesis in the eruption. The phenomenon of spot development following the appearance of an eruption is so general that it is possible upon the appearance of an isolated eruption to predict with certainty the advent of a spot. When the spot is well developed it stimulates new eruptions. The recent paper by Hale[1] depicts beautifully the vortices in the hydrogen about the spots. My $H\alpha$

[1] *Astrophysical Journal*, 28, 100, 1908.

PLATE XIX

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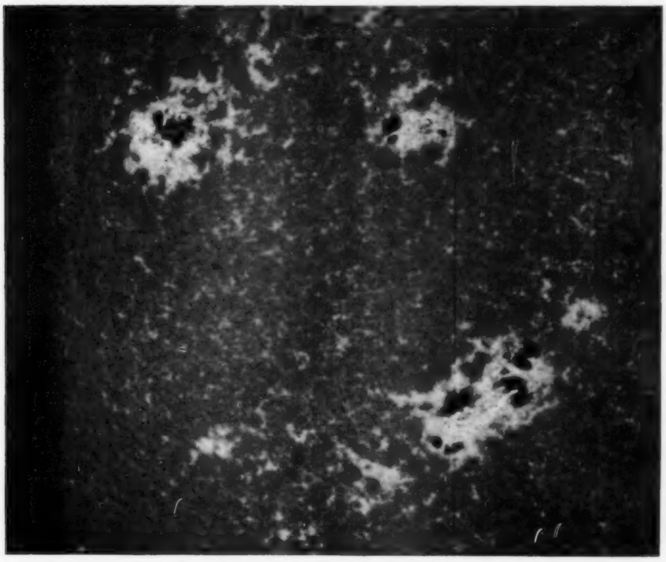

W

FIG. 3.—CALCIUM PLATE OF AUGUST 3, 1908, SHOWING CHAIN OF ERUPTIONS BETWEEN SPOTS OF SOUTHERN GROUP. ORIGINAL SIZE

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FIG. 4.—HYDROGEN PLATE OF AUGUST 3, 1908, SHOWING LOCATION OF ERUPTIONS. ORIGINAL SIZE

PLATE XX

N

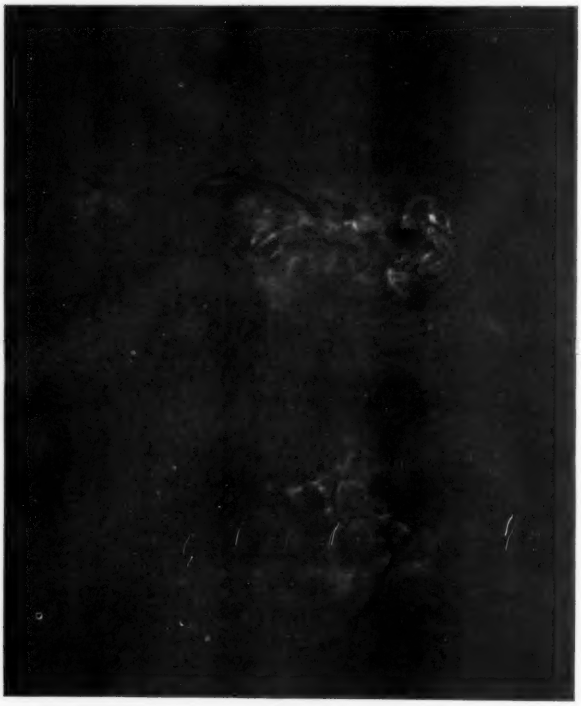
E  W

FIG. 5.—HYDROGEN PLATE OF AUGUST 31, 1908, SHOWING OPPOSITELY DIRECTED VORTICES IN THE TWO HEMISPHERES. ORIGINAL SIZE

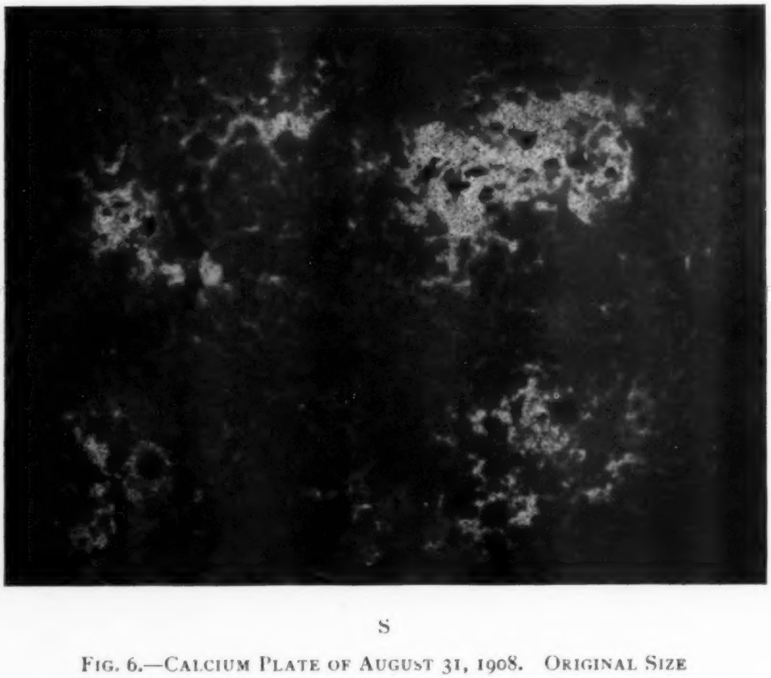
E  W

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FIG. 6.—CALCIUM PLATE OF AUGUST 31, 1908. ORIGINAL SIZE

plates show that the vortices form early in the life of the spot. I obtained no $H\alpha$ plate on September 4, the birthday of the south following spot of Fig. 2, but on an $H\alpha$ plate of September 5, the vortex is well developed. Careful examination of this spot in calcium radiation, Fig. 2, shows the whirl on September 4. It may be stated here that many of the spots having hydrogen in well-marked vortices about them furnish also unmistakable signs of whirl of calcium vapor. The cooler matter from above seems to be drawn down into the spots. Here it may cool and contract the gases and cause an uprush of hotter, lighter gas from below, and, as suggested by Faye, the cooler, descending gas rapidly heating and expanding may also return violently to the surface. Perhaps the eruption between the spots of a well-developed group may be in part excited by the interference of the whirls.

However the eruptive prominences arise, their location between the spots and their absence in front of the leader spot and behind the follower need an explanation, and in seeking it we must consider the proper motions of the members of the group and the circulation about them.

Examination of all of the $H\alpha$ plates and the record of earlier observed whirls in the calcium vapors results in assigning the direction as counter-clockwise in the northern hemisphere and clockwise in the southern. This is in agreement with the demands of Faye's theory. The whirl about the follower spot is seldom so well marked as about the leader. In fact, it seems questionable whether the follower ever develops a perfect whirl of its own. The direction of motion about the follower and its functions generally in the group must be carefully investigated.

Figs. 5 and 6 (Plate XX) show the details of motion about the spots of two great groups. The plates were obtained on August 31, 1908, the $H\alpha$ plate, Fig. 5, at $5^h\,57^m.0$ G.M.T. and the calcium plate which is given for comparison at $3^h\,28^m.7$ G.M.T. The spots are those of Figs. 2, 3, and 4 on their return to the center of the disk. The small, newly born, north preceding spot of Fig. 4 now far surpasses its southern neighbor in size and activity. A few points deserve attention. The direction of motion, opposite in the two hemispheres, is apparent, though the outer part of the quiescent prominence rather masks the whirl of the southern spot. The lack of definite stucture of hydrogen

flocculi in the midst of the great group is shared by nearly all large groups. The structure is almost as chaotic as in the calcium flocculi, the overlying quiescent prominences only are more clearly shown. The large quiescent prominence reaching into the northern group from the north and rear changed very slowly in form; finally it parted near the middle on September 1 and dissolved. I cannot say that it was drawn into the maelstrom. The quiescent prominence to the south of the southern spot persisted for several days. It was present in different form on August 27, and was still present on September 5, when the spot was near the western limb. I have examined the plates to see if here might not be another instance of a prominence being drawn into a spot, similar to that observed by Hale.[1] Part of it may have been and probably was drawn into the spot, but the evidence is inconclusive and on August 31 and succeeding days seems to be negative. It should be borne in mind that the prominence does not need to reach the umbra or even penumbra in order to be drawn in, but probably descends into the whirl at a considerable distance from them.

In conclusion I wish to express my thanks to Professor Slocum of Brown University for assisting me in obtaining the negatives of Fig. 1 and to Dr. Giorgio Abetti for similar help on the originals of Figs. 2 and 6.

Yerkes Observatory
September 20, 1908

[1] *Loc. cit.*

EFFECT OF INCREASING THE SLIT-WIDTH UPON THE ACCURACY OF RADIAL VELOCITY DETERMINATIONS

By J. S. PLASKETT

The result of an investigation recently undertaken at Ottawa[1] has shown that the exposure time required for star spectra in average seeing is almost inversely proportional to the slit-width until this reaches at least 0.075 mm. This is partly due to losses by diffraction at the slit-jaws but mainly to the enlargement of the star image by atmospheric disturbances, the paper above cited having shown that the effective diameter of the star image, even with the shortest exposures, is rarely less than 2″, about 0.055 mm, at the focus of the Ottawa refractor. Whatever the cause, however, the fact remains that a considerable saving in time and increase in output can be effected by an increase in slit-width. It therefore becomes a question of much interest to determine how far the accuracy of velocity determinations is affected by such increase. This can only be satisfactorily obtained from actual trial, and it is the purpose of this paper to attempt a partial solution of the problem.

There are three ways in which an increase in slit-width may lead to loss of accuracy in velocity determinations:

a) By the decrease in purity and consequent difficulty of identification of lines and determination of the blended wave-lengths.

b) By increased diffuseness and breadth of the spectral lines and consequent probable increase of errors of measurement.

c) By systematic displacements of the lines as a whole, with consequent error in the velocity, due to asymmetric position of the star image within the slit opening.

If, as in this case, the investigation is limited to early-type spectra, where the lines are single, loss of purity will have very little effect and case (*a*) may be omitted from consideration. Even in spectra of the solar type where ordinarily high purity is desirable, it seems

[1] *Astrophysical Journal*, **27**, 139, 1908.

likely that, if measured on the spectrocomparator, the loss of accuracy will be due mainly to increase in the accidental errors of setting.

Limiting ourselves therefore to the two sources (*b*) and (*c*) of error, it is evident that they are in a sense entirely independent of each other. The former may be evaluated without considering the latter by treating the residuals from the measures of the star lines on a sufficient number of plates, the residuals for the lines on each plate being obtained from the mean velocity for that plate. The effect of the latter can be obtained only from such a number of complete velocity determinations, that the systematic displacements due to source (*c*) may be considered accidental. Even then the effect will be masked by the accidental errors of measurement due to cause (*b*) and possibly by systematic displacements due to other causes. Again, in source (*b*) it is evident that the width and diffuseness of the lines depend upon the relative lengths of camera and collimator, equal focal lengths evidently giving more diffuse lines than in the case where the collimator is longer than the camera. This and other considerations led to the test being made with three dispersions of the spectrograph. The collimator focus was 525 mm in each case.

I. One-prism spectrograph, Brashear Single Material camera objective of 525 mm focus; linear dispersion 30.1 tenth-meters per millimeter at $H\gamma$.

II. Three-prism spectrograph, Zeiss "Chromat" camera objective of 525 mm focus; linear dispersion 10.2 tenth-meters per millimeter at $H\gamma$.

III. Three-prism spectrograph, Ross "Homocentric" camera objective of 275 mm focus; linear dispersion 18.2 tenth-meters per millimeter at $H\gamma$.

In the last dispersion, the Ross camera lens was not free from aberration and curvature of field; moreover, owing to a temporary mounting no temperature control could be applied. Results in this case were consequently considered less worthy of confidence, and only three slit-widths, 0.025, 0.051, and 0.076 mm, were tested as compared with four, 0.025, 0.038, 0.051, and 0.076 mm, in dispersions I and II.

The star chosen for the experiments was *β Orionis*, which contains several lines of only moderate sharpness, thus making the test

as general as possible, obtaining, so far as may be from one star, the effect of increasing the slit-width upon the accuracy of measurement of both sharp and diffuse lines. Its brightness is such as to render only short exposures necessary, although, as will be seen later, this may not be an advantage so far as systematic displacements due to cause (*c*) are concerned.

It may be of interest to give the average exposures required for the different slit-widths in the three dispersions, as indicating the time saved by the use of the wider slits.

Dispersion	Exposure Time for Slit-Widths			
	0.025	0.038	0.051	0.076
I...........	2.5 min.	1.5 min.	1 min.	0.75 min.
II...........	14	10	8	5
III...........	5		3	2

Although it was recognized that more trustworthy results would have been obtained by double the number, the spectra made at each slit-width, owing to the labor involved in the measurement, were limited to six. Of the 66 plates, 18 were measured by Mr. Harper, the balance by myself. About 15 lines, star and comparison, were measured on each plate which, with eight settings to the line, makes nearly 8000 settings of the micrometer screw.

The same lines, both star and comparison, were measured on all plates of the same dispersion, but these lines changed as the dispersion changed, owing to the longer range in the single-prism instrument and to differences in the best lines available in the other two cases. The lines *Mg* 4481.400, *He* 4471.676, and $H\gamma$ were measured in all the spectra. There were measured, in addition, in the single-prism plates $H\delta$, *He* 4026.352, and K; in the three-prism plates with the short-focus camera *Si* 4131.047, *Si* 4128.211, and $H\delta$, and in the three-prism plates with the long-focus camera *He* 4388.100. In some of the latter the lines 4131, 4128, and $H\delta$ were also measured.

All measures were reduced to velocities by a modification of Hartmann's method.[1] Each line was weighted during the measurement and the velocity of the plate obtained from the weighted mean. As

[1] *Astronomische Nachrichten*, **155**, 110, 1901.

stated before, the residuals for each line in the plate were obtained from the weighted mean of that plate, and the residuals of all the lines in the six plates of a series were treated to obtain the relative accuracy of that series. It is evident that the probable error of a line of unit weight will not necessarily give the relative accuracy of the series, as the weights given to the lines in different series may not be consistent. Hence it has seemed preferable to obtain the probable error of a line of average weight as a measure of the relative accuracy of a series, so far as it depends upon accidental errors of measurement.

For systematic errors due to asymmetric position of the star image with respect to the slit-jaws, the best that can be done is to obtain the probable error of a plate from the six plates of a series. Although the number of measures is too small, and the plates are affected with accidental errors as well as possible systematic displacements due to other causes, nevertheless the relative values for different slit-widths will indicate whether systematic displacement is liable to occur when the slit is widened.

These probable errors are obtained from two or three groupings of the lines in each dispersion. The three lines 4481, 4472, and 4341 formed one group in all the plates. In addition in the single-prism plates a group of all the seven lines was formed; in the three-prism long focus, of the four lines 4481, 4472, 4388, and 4341; and in the three-prism short focus two additional groups (*a*) of the lines 4481, 4472, 4341, 4131, and 4128, (*b*) of all the seven lines measured.

These different groupings entailed little additional labor and served to give some idea of the relative values of the lines.

The three lines 4481, 4472, 4341 are of by far the best quality for measurement in all the plates, and besides are near the position of minimum deviation, λ 4415, the axis of the camera lens and the point of minimum focus or turning-point of the color-curve of objective and corrector. As will be seen, the probable errors are considerably smaller when these three lines only are used than when they are combined with others of poorer quality.

It has not seemed necessary in this case to tabulate the separate measures, but only to give the probable errors in kilometers per second of the different series for the different groupings of lines.

ERRORS

Dispersion	Slit-Width	Probable Error Line of Average Weight			Probable Error Single Plate		
		3 Lines		7 Lines	3 Lines		7 Lines
	mm						
One Prism	0.025	4.6		5.3	1.7		1.3
Camera of 525 mm focus	.038	2.5		4.8	2.7		2.5
	.051	2.4		5.2	3.0		1.5
	.076	4.4		7.5	7.7		5.2
		3 Lines	4 Lines		3 Lines	4 Lines	
Three Prisms	.025	2.3	2.3		1.5	1.7	
Camera of 525 mm focus	.038	2.1	2.8		1.3	1.2	
	.051	2.5	3.0		0.7	0.8	
	.076	2.1	3.1		0.9	1.4	
		3 Lines	5 Lines	7 Lines	3 Lines	5 Lines	7 Lines
Three Prisms	.025	2.9	2.8	5.6	2.1	3.2	2.4
Camera of 275 mm focus	.051	2.9	3.2	4.8	3.0	3.8	4.2
	.076	3.8	4.0	6.4	2.9	3.8	5.0

The above summary of probable errors shows some curious and unexpected results.

With the single-prism spectrograph, the accidental error of setting as measured by the probable error of a line of average weight shows no increase for increase of slit-width from 0.025 to 0.051 mm, but a further widening to 0.076 mm causes an increase of about 50 per cent. in the accidental errors. The error due to non-central position of the star image within the slit-jaws, as measured by the probable error of a plate, shows an even more marked increase of about 200 per cent. with a slit 0.076 mm wide. As the exposures for this width were only about 45 seconds each, it is probable that, during an exposure, the star image was not on the whole centrally situated, causing systematic displacements of the star lines, variations in the velocities of the plates, and consequent increase of probable error. A position 0.004 mm to one side of the center would cause an error of about 10 km. If the exposure had been longer, the vagaries of seeing and guiding would probably insure a mean position nearly central and consequent freedom from systematic error. This is well shown in the higher dispersions, where the exposure times were 6 and 2.5 minutes and where, in the former, the systematic error for slit-width 0.076 mm is less than for slits 0.025 and 0.038 mm. It may be of interest to mention in this connection an apparent system-

atic difference between the velocities obtained with wide and narrow slits. They show on the whole a smaller positive value of about 2 km for the wider slit-widths. This may be due to a personal error in guiding or to some peculiarity in the optical path from the slit to the eye which systematically causes the image to be held to one side of the center of the opening.

With the three-prism spectrograph and the 525 mm camera neither accidental nor systematic errors show any increase with increase of slit-width, and so far as stars of this type are concerned apparently as accurate measures and as reliable results can be obtained with a slit 0.076 mm wide as with 0.025 mm. The exposure time in the former case is only about one-third that of the latter thus allowing a considerable increase of output.

With three prisms and 275 mm camera there is a slight increase in the errors with increase of slit-width but this is not marked and may be partly accounted for by the aberration of the lens and the lack of temperature control.

Summarizing the whole question we may conclude that, in early-type stars, a slit at least 0.051 mm wide may be used without appreciably increasing the errors of setting on the lines or introducing any systematic displacement. In the case of the higher dispersions the slit may be widened to 0.076 mm without diminishing the accuracy of velocity determinations. The same thing may also be true in single-prism work with fainter stars where the exposure will be longer than a few minutes. It must not, however, be forgotten if the spectrum has faint metallic lines as in *Sirius* or *Vega*, that an increase in slit-width will diminish the contrast, and, with a slit as wide as 0.076 mm, will cause the fainter lines to disappear.

A study of the residuals leads to some other interesting points to which, although foreign to the subject of this paper, I may just briefly refer.

The residuals of $H\delta$ from 18 plates with the single-prism and 12 plates with the three-prism spectrograph give a mean correction to wave-length 4102.000 of -0.152 tenth-meters, showing a change in the same direction although of slightly greater magnitude than that adopted by Campbell and Wright.[1] However, owing to the character

[1] *Astrophysical Journal*, 9, 50, 1899.

of the spectrum, considerably greater weight should be attached to their values.

The residuals from $H\beta$ are so high and so irregular, being sometimes positive and sometimes negative with all three dispersions and all slit-widths, that no confidence can be placed in the measurement of this line and it would be preferable to omit it. This may be, in part, due to the character of the line itself, and in part, to the fact that the star image is considerably out of focus at $H\beta$, resulting in an enlarged disk and consequent non-uniform illumination of the collimator and camera lenses. There is also at this part of the field considerable vignetting of the pencil, which will not help matters.

In the case of lines to the violet end, however, the residuals do not indicate any systematic difference nor are they of greater magnitude than is to be expected from their character. The star focus in this case is not so far beyond the slit, and besides the vignetting does not affect them to so great an extent.

In conclusion, it gives me pleasure to acknowledge the interest shown and encouragement given in this work by the director, Dr. W. F. King.

DOMINION OBSERVATORY, OTTAWA
August 1908

THE SPECTROSCOPIC BINARY ψ *ORIONIS*

By J. S. PLASKETT

The star ψ *Orionis* ($\alpha = 5^h\ 21^m.6$; $\delta = +3°\ 1'$; Phot. Mag. 4.5) was announced as a spectroscopic binary by Frost and Adams[1] in 1903. Upon learning from Mr. Frost that its orbit was not under investigation at the Yerkes Observatory, it was placed under observation here on November 11, 1907. The last of the 40 plates secured was made on March 16, 1908, and all of these except three, which were too weak for measurement, have been used in the determination of the orbit. The instrument used was the single-prism spectrograph of the Dominion Observatory which has a linear dispersion of 30.2 tenth-meters per millimeter at $H\gamma$ and gives the whole visible spectrum in sharp focus. A visual objective and correcting lens, however, limits the usable region to that between and including $H\beta$ and K.

The spectrum of ψ *Orionis* is of the helium type with very broad and diffuse lines of helium and hydrogen. Their measurement is difficult and the resultant velocities subject to considerable uncertainty, a measure of this being given by the probable error, ± 6.8 km, of an observation of unit weight. The lines, although diffuse, are in general fairly symmetrical and in consequence more easily measured than in the case of ι *Orionis* recently discussed.[2] Furthermore, owing to the extremely high range in the velocity, about 288 km, and to the low eccentricity, the elements of the orbit can be satisfactorily determined notwithstanding the high probable error of a plate.

The lines measured in the spectrum of ψ *Orionis*, with the velocities corresponding to one revolution of the micrometer screw (0.5 mm pitch) are given in the accompanying table.

The lines λ 4713 and λ 3970 were not often measurable and have been used only a few times. The number of lines measured varied from 4 to 9, except that in one plate only 3 were used. Most of the

[1] *Astrophysical Journal*, **17**, 246, 1903.

[2] *Ibid.*, **27**, 272, 1908.

TABLE I

LINES IN ψ *Orionis*

Element	Wave-Length	Velocity per Revolution
$H\beta$	4861.527	1451.
He	4713.308	1332.
He	4471.676	1143.
He	4388.100	1080.
$H\gamma$	4340.634	1044.
He	4143.928	898.
He	4120.973	881.
$H\delta$	4102.000	868.
He	4026.352	814.
$H\epsilon$	3970.177	774.

measures have been made by myself, although I am indebted to Mr. Harper and Mr. Westland for the measures of several and for the remeasurement of some giving larger than normal residuals. The velocities were generally only slightly changed by the second measurement.

The data of the 37 plates are given in Table II, the phase being obtained from the period finally determined, 2.52588 days, using for initial epoch Julian day 2,417,914.0.

The determination of the period entailed some difficulty and it was not until about 25 plates had been measured that an approximate value was obtained. High positive and negative velocities repeated themselves every 5 days, but this period would not suit intermediate values. A trial of 2.5 days showed traces of periodicity which was enhanced by slightly lengthening. Finally, the Ottawa observations, extending over 50 periods, grouped themselves most favorably under a value of 2.526 days which agreed well with the three 1903 observations of Frost and Adams, the effect of introducing the latter being to slightly diminish the value. For a preliminary value 2.526 days was chosen.

Following the practice here and elsewhere for stars of this type, in which accurate velocities are unobtainable, the elements of the orbit were first determined by graphical methods, different values being rapidly tested by the method of Dr. W. F. King.[1] After considerable adjustment, satisfactory elements, which agreed well with

[1] *Astrophysical Journal*, **27**, 125, 1908.

TABLE II

MEASURES OF ψ *Orionis*

Plate No.	Julian Date	Phase	Velocity	No. of Lines
1138	2,417,891.836	.569	+ 41.7	8
1158	903.717	2.347	−145.5	4
1182	914.830	.830	+135.8	9
1183	914.857	.857	+139.1	8
1195	938.667	1.934	− 45.5	8
1196	938.698	1.965	− 70.2	8
1208	942.764	.979	+145.9	8
1209	942.792	1.007	+148.0	8
1214	944.639	.328	− 7.0	8
1215	944.667	.356	− 5.0	9
1220	954.726	.312	− 5.5	7
1221	954.750	.336	− 11.6	6
1227	955.556	1.142	+143.0	8
1233	957.496	.556	+ 51.0	7
1238	961.539	2.073	−114.5	7
1239	961.578	2.112	−117.2	7
1257	963.645	1.653	+ 16.5	6
1264	964.585	.067	−101.2	6
1271	965.534	1.016	+139.9	7
1279	968.487	1.444	+116.2	5
1283	968.598	1.555	+ 56.6	5
1296	970.459	.890	+144.5	6
1301	970.626	1.057	+153.8	4
1304	970.710	1.141	+151.6	5
1312	975.556	.935	+145.3	7
1317	980.542	.869	+126.0	8
1319	980.677	1.004	+140.5	6
1321	989.534	2.283	−140.4	8
1333	990.510	.734	+103.9	6
1334	992.547	.245	− 49.0	6
1336	993.667	1.365	+103.3	5
1344	994.499	2.197	−136.7	6
1347	994.685	2.383	−135.1	6
1349	996.531	1.703	+ 34.3	7
1376	8,005.643	.711	+110.2	3
1384	010.642	.659	+ 95.6	5
1395	017.510	2.475	−135.0	7

the observations, were obtained. A diagram of the corresponding velocity-curve with the observations shown as circles appears in Fig. 1.

The elements of the orbit are:

$$\begin{aligned} \text{Period} &= 2.526 \text{ days} \\ e &= 0.063 \\ \omega &= 186^\circ \\ K &= 147.2 \text{ km} \\ \gamma &= +12.42 \text{ km} \\ a \sin i &= 5{,}103{,}000 \text{ km} \\ T &= 2.36 \text{ days} = \text{Julian Day } 2{,}417{,}916.36 \end{aligned}$$

This solution had been completed and was considered final when Dr. Schlesinger, to whom I am much indebted for this and other valuable suggestions, advised the application of a least-squares correction to the orbit of *ι Orionis*. Without having given much consideration to the matter, and influenced probably by the practice of other observers in stars of similar type, it had always appeared to

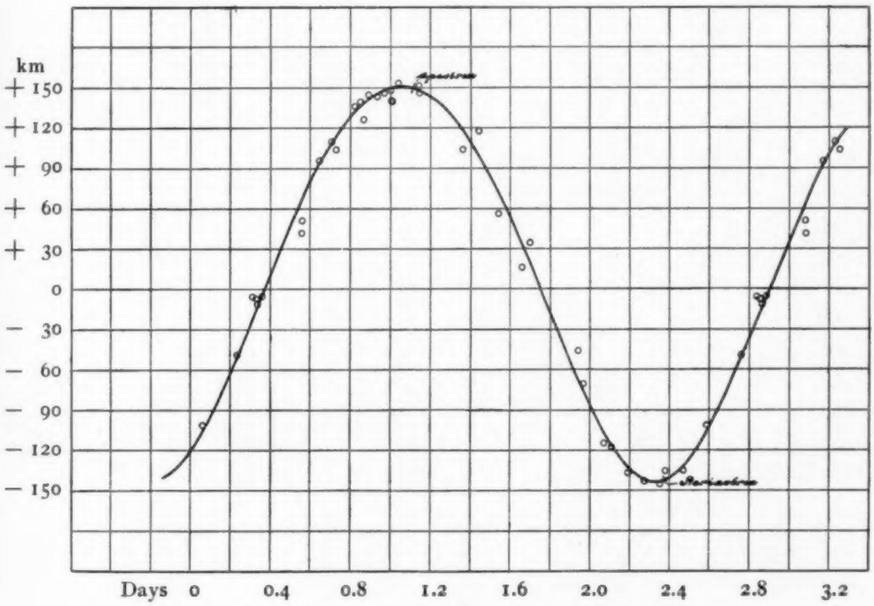


FIG. 1.—Preliminary Velocity-Curve of *ψ Orionis*.

me that in observations with high residuals not much would be gained. However, such a correction applied to *ι Orionis* (see p. 274) showed a large reduction of Σpvv and it was thought desirable to make a similar solution for *ψ Orionis*.

It will be noticed that by far the highest residuals occur in the ascending and descending branches of the curve. This may be due to an error in the period or to the fact that, owing to changes in the seeing or to clouds during part of the exposure, the effective mean date of these exposures is not the same as the actual mean time entered. This latter cause might have considerable effect in a star of short period. Taking cognizance of the former cause, it was

deemed advisable to consider at first the Ottawa observations only and to obtain from them, if possible, a correction to the period.

Reducing the 37 observations to 29 places by combining plates taken successively on the same nights, weighting them accordingly, and computing from each, by the elements obtained above, the coefficients for the five unknowns (method of Lehmann-Filhés[1]) with the addition of an unknown, of coefficient unity, for the velocity of the system, we obtain 29 observation equations connecting these six unknowns with the residuals between the observed and computed values of the velocity. To make the observation equations homogeneous the following substitutions were made:

$$x=\delta K \qquad u=\frac{100K}{(1-e^2)^{\frac{3}{2}}}\delta\mu=14801.7\delta\mu$$

$$y=K\delta e=147.2\delta e \qquad v=\frac{K\mu}{(1-e^2)^{\frac{3}{2}}}\delta T=368.18\delta T$$

$$z=K\delta\omega=147.2\delta\omega \qquad w=\delta\gamma$$

There result the following normal equations:

$$\begin{aligned}
20.398x-5.255y+2.618z+.471u-2.431v+5.297w+85.859&=0\\
+20.726y+1.446z+.288u-1.687v-5.132w-31.490&=0\\
+15.514z+7.241u-15.392v+4.702w+55.912&=0\\
+5.291u-7.169v+1.401w+13.180&=0\\
+15.337v-4.291w-54.156&=0\\
+37.000w+38.800&=0
\end{aligned}$$

It will be noticed that the normals in z and v ($\delta\omega$ and δT) are practically identical and it will be impossible accurately to determine their values separately owing to the smallness of the coefficients in the elimination. Consequently $\delta\omega$ and δT were successively assumed to be zero, and we obtain the following corrected elements from the two solutions.

	Preliminary	For $\delta T=0$	For $\delta\omega=0$
K	147.2	143.843	143.799
e	0.063	0.06992	0.07012
ω	186°	183°.736	186°
Period U	2.526 days	2.52561	2.52563
T	2.36 days	2.36	2.3753
γ	+12.42	+12.517	+12.453

[1] *Astronomische Nachrichten*, **136**, 17, 1894.

As there is relatively less change in T than in ω in the two cases, the first set only will be considered.

The change in the period is small, showing that no improvement can be effected in the Ottawa observations by any marked change in this variable and it can now be finally determined by means of the three early observations of Frost and Adams with the aid of three additional plates kindly sent me by Mr. Frost. Two of the latter, the third being unsuitable, were carefully measured by Mr. Harper and the use of the five measures, three of 1903, one each of 1904 and 1905, gave as the only permissible period 2.52588 days, which cannot be in error more than one unit in the last place. The positions of these observations on the curve are shown by the crosses in Fig. 2. The residuals are no larger than is to be expected from spectra so uncertain and difficult of measurement as these.

In the final solution, then, a correction for the period was omitted. As provisional elements (in round numbers) those obtained by the first solution were taken.

$$\begin{array}{ll} \text{Period}=2.52588 \text{ days} & \omega=185^\circ \\ K=144.0 & T=2.36 \text{ days} \\ e=0.07 & \gamma=+12.5 \text{ km.} \end{array}$$

The observations with their corrected phases, given in Table II, were grouped into 19 normal places (Table III), from which were obtained 19 observation equations. Using the same substitutions for homogeneity as before there result the normal equations

$$\begin{array}{llllll} 20.556x & -5.145y & +2.629z & -2.397v & +5.351w & -1.617=0 \\ & +20.106y & +1.334z & -1.600v & -5.639w & +13.118=0 \\ & & +15.614z & -15.465v & +4.656w & +14.165=0 \\ & & & +15.398v & -4.282w & -13.127=0 \\ & & & & +37.000w & +16.670=0 \end{array}$$

Again the normals in z and v are nearly identical. Assuming V or $\delta T=0$ the solution gives

$$\begin{array}{ll} x=+0.1198 & \delta K=+0.1198\pm 1.582 \text{ km} \\ y=-\ .7099 & \delta e=-\ .00493\pm .01116 \\ z=-\ .7225 & \delta\omega=-\ .005015=-.286^\circ\pm .710^\circ \\ w=-\ .4851 & \delta\gamma=-\ .4851\pm 1.177 \text{ km} \end{array}$$

giving for the final elements:

$$K=144.12\pm1.58 \text{ km}$$
$$e=0.0651\pm\ .0112$$
$$\omega=184^\circ.71\pm\ .71^\circ$$
$$U=2.52588 \text{ days}$$
$$T=2{,}417{,}916.36 \text{ Julian date}$$
$$\gamma=+12.015 \text{ km}\pm1.177 \text{ km}$$
$$a \sin i=4{,}995{,}100 \text{ km.}$$

TABLE III

NORMAL PLACES

No. of Plates	Total diff. of phase	Mean phase from T	Mean Velocity	Wt.	C.—O. Preliminary	C.—O. Final	Eph.—Equation
2........	.036	.005	−140.3	2	− 2.7	− .5	.00
1........		.115	−135.0	1	+ 6.6	+ 5.4	+.18
1........		.233	−101.2	1	− 2.5	− 2.7	+.02
1........		.411	− 49.0	1	+ 4.1	+ 2.0	−.17
4........	.044	.499	− 7.3	4	− 4.6	− 7.5	−.02
2........	.013	.7285	+ 46.4	2	+22.9	+18.6	−.05
1........		.825	+ 95.6	1	+ 1.5	− 2.9	−.08
2........	.023	.8885	+107.0	2	+ 5.9	+ 1.1	−.03
3........	.039	1.018	+133.6	3	− .1	− 1.6	−.02
3........	.089	1.101	+144.7	3	+ 1.0	− 3.3	−.01
4........	.053	1.187	+145.6	4	+ 4.5	+ .7	−.01
2........	.001	1.3075	+147.3	2	+ .1	− 2.8	.00
2........	.079	1.5705	+109.7	2	− 2.6	− 2.7	+.05
1........		1.711	+ 56.6	1	+12.0	+13.4	−.04
2........	.050	1.844	+ 25.4	2	− 1.1	+ 1.7	+.01
2........	.031	2.1155	− 58.2	2	−14.6	−10.3	−.02
2........	.039	2.2585	−115.8	2	+ 1.2	+ 5.4	−.01
1........		2.363	−136.7	1	+ 1.8	+ 5.2	+.25
1........		2.449	−140.4	1	− 2.7	+ .3	−.08

A comparison (Table III) of the residuals obtained on the one hand by computing an ephemeris from these elements and on the other by substituting the values of the unknowns in the observation equations shows that the solution is satisfactory. The resulting velocity-curve with the normal places plotted as circles is given in Fig. 2. Σpvv is reduced from 1970.3 to 1522.5, the probable error of an observation of weight unity from ±7.7 km to ±6.8 km. The only change from the original elements of appreciable magnitude is in K which is reduced by about 3 km. Three rather high residuals, all occurring on the inclined parts of the curve, may account for part of this change. As previously mentioned, part of the discrep-

ancy in these three places, beyond that due to the character of the spectrum, may be explained, in a very short period binary, by inaccuracy in phase determination due to unsymmetrical exposure. The very large range of velocity, 288 km, the highest in this type of binary known to the writer, is undoubtedly a considerable factor in obtaining

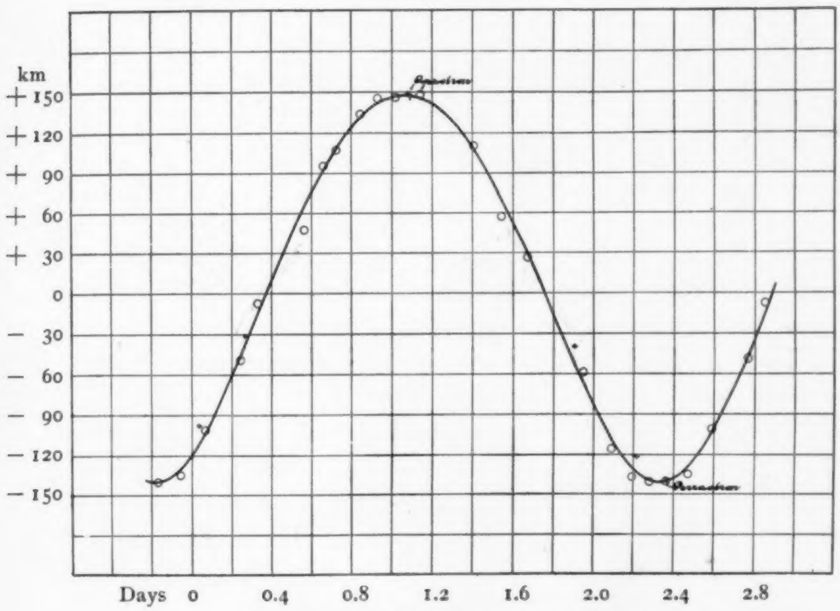


FIG. 2.—Final Velocity-Curve of ψ *Orionis*

satisfactory elements which in this case may be considered as fairly closely determined. Apparently, as in ι *Orionis*, the least-squares solution has improved the geometrically determined elements.

In conclusion I wish to express my obligations to the director, Dr. W. F. King, for the advice he has given and the interest he has shown in this work.

DOMINION OBSERVATORY, OTTAWA
July 1908

THE ORBIT OF ι *ORIONIS*

By J. S. PLASKETT

Acting on a suggestion kindly made to me by Dr. Schlesinger, a least-squares solution has been applied to the elements of the orbit of ι *Orionis* recently published in this *Journal*.[1] As preliminary elements those determined in the above paper were taken, and the 113 plates were grouped into 26 normal places, the same as before except for some minor changes introduced by a consistent system of weighting. An ephemeris having been computed from these elements, the coefficients of the unknowns in the observation equations were calculated from the formulae of Lehmann-Filhés[2] for each of these places. The period was considered as very closely determined by the method previously used and a correction considered unnecessary.

From the observation equations were formed the normal equations below, the following factors being introduced for homogeneity:

$$x=\delta K$$
$$y=K\delta e=112\delta e$$
$$z=K\delta\omega=112\delta\omega$$
$$u=\frac{K\mu}{(1-e^2)^{\frac{3}{2}}}\delta T=83.46\delta T$$
$$v=\delta\gamma$$

NORMAL EQUATIONS

$$\begin{array}{rrrrrr}
+44.968x & -29.522y & +3.322z & +0.327u & -14.291v & +98.606=0 \\
 & +228.507y & -41.899z & +65.630u & +39.089v & -244.074=0 \\
 & & +51.724z & -53.431u & -33.929v & -33.442=0 \\
 & & & +76.940u & +25.424v & -56.373=0 \\
 & & & & +95.000v & -15.800=0
\end{array}$$

The solution of these equations gave the following corrected elements:

[1] *Astrophysical Journal*, **27**, 272, 1908.

[2] *Astronomische Nachrichten*, **136**, 17, 1894.

	Preliminary	Corrected
K	112.0	109.92
e	0.75	0.7552
ω	110°	113°31
T	1.94 days	1.991 days
γ	+20.7 km	+21.34 km
Period	29.136 days	29.136 days
$a \sin i$	29,680,000 km	28,867,000 km

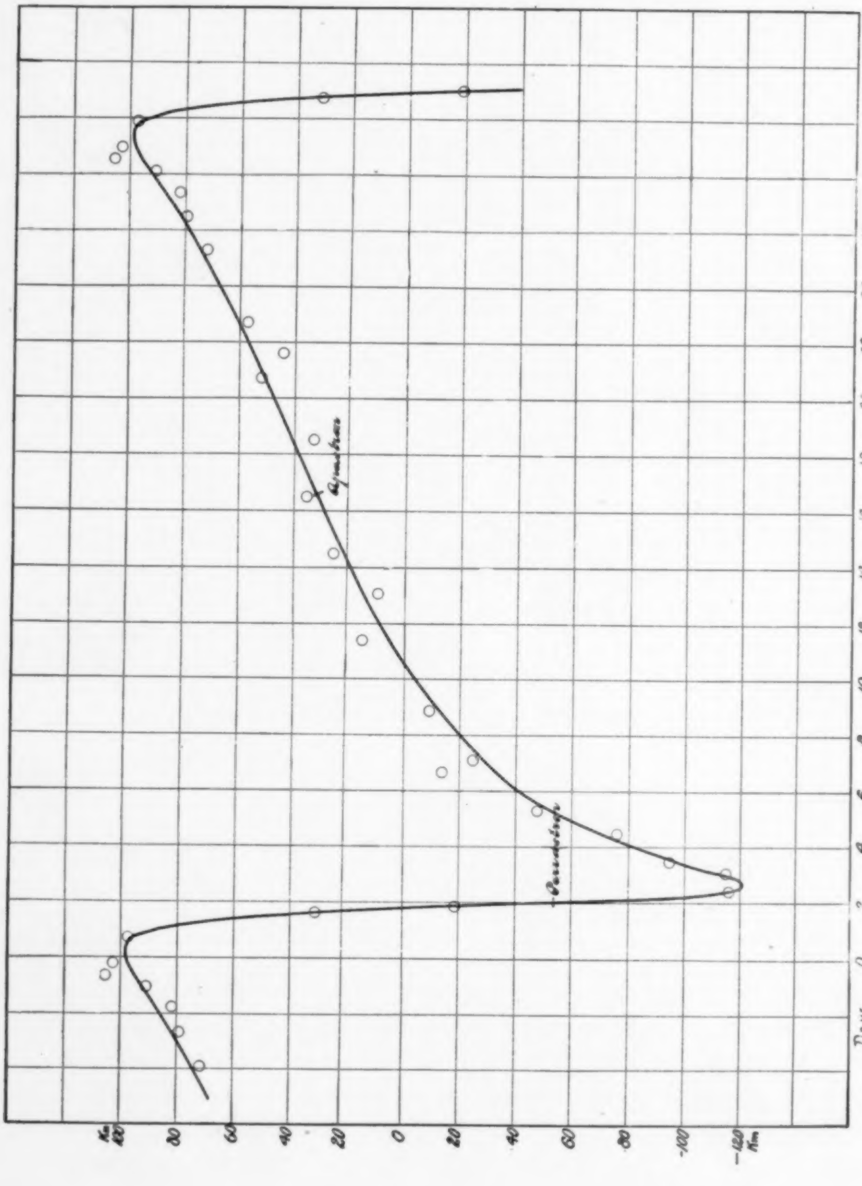
A comparison of the residuals obtained from an ephemeris and from substitution in the observation equations showed some differences of over a kilometer and a second solution was necessary. For preliminary elements those obtained in the first solution, except T, which was increased to 2.01 days, were used. The change in T was due to a better agreement thereby produced in the residuals. Using the same substitutions for homogeneity there result the normal equations

$$\begin{array}{rrrrrr}
+45.058x & -28.047y & +2.576z & +0.726u & -14.660v & -0.731=0 \\
 & +266.994y & -45.686z & +65.208u & +43.697v & +117.502=0 \\
 & & +50.372z & -48.247u & -33.053v & -70.762=0 \\
 & & & +64.085u & +22.897v & +95.820=0 \\
 & & & & +95.000v & +34.800=0
\end{array}$$

Their solution gives for final elements the following:

K	109.90 ±1.100 km
e	0.7543± .0046
ω	113°28 ±1°083
T	1.993 ± .022 days = Julian Day 2,417,587.993
γ	+21.34 ±0.856 km
Period	29.136 days
$a \sin i$	28,907,000 km

An ephemeris computed from these elements shows that Σpvv has been reduced from 2994 to 2181, the probable error of an observation of unit weight becoming ±6.88 km, while the probable errors of the elements become those given above. The changes from the first solution are very small but the agreement between the residuals is now satisfactory. The velocity-curve corresponding to the final elements is given in the accompanying figure, with the positions of the normal places as small circles. A comparison of



Velocity-Curve of ι *Orionis*

this with the previous figure shows that the general trend of the observations is more closely followed. The probability of a secondary disturbance seems somewhat less than with the original elements, and this is further lessened by a knowledge of the fact that the normal places with the highest residuals contain always one or more observations with the universal spectroscope where the temperature control was poor and the spectra contained only two measurable lines.

The result of this computation seems to justify Dr. Schlesinger's contention that, even in the case of spectra in which accurate measurement is impossible, the least-squares solution will give the best determination of the elements of a binary orbit.

Dominion Observatory, Ottawa
July 1908

PHOTOGRAPHIC LIGHT-CURVE OF THE VARIABLE STAR *SU CASSIOPEIAE*

By J. A. PARKHURST

The variation of this star (R. A. $2^h\ 43^m\ 2^s.9$; Dec. $+68^\circ\ 28'\ 28''$ [1900]) was discovered by Müller and Kempf[1] from the discordance in their results obtained in 1903 and 1905 for the *Photometric Durchmusterung*. It received the provisional number 155.1906, and their measures (together with those by Graff) were published in December 1906.[2] Before this was received, a note by the writer, confirming the variation, was sent to the printer.[3] Lastly, von Zeipel[4] has published 23 measures with a Zöllner photometer made between February 16, 1907, and January 24, 1908.

As this star is within one degree of the *Algol*-type variable *RZ Cassiopeiae*, the plates taken for the latter by the extra-focal method and described in detail by Jordan and the writer[5] also serve to show the changes of *SU*.

The comparison stars used, as in the measures of *RZ*, were

B. D.	Potsdam Color Mag.	Adopted Spectrum Mag.
F $+67^\circ$ 224	GW 6.15	A 6.15
D $+69^\circ$ 171	.. ....	A 7.45

More plates were used than in the measures of *RZ* given in the article last quoted. A remeasurement of these plates, reduced with an improved absorption curve, gave by the method of the "absolute photographic scale" an interval of 1.30 magnitudes between the

[1] *Potsdam Publications*, **16**, 254.

[2] *Astronomische Nachrichten*, **173**, 305, 1907.

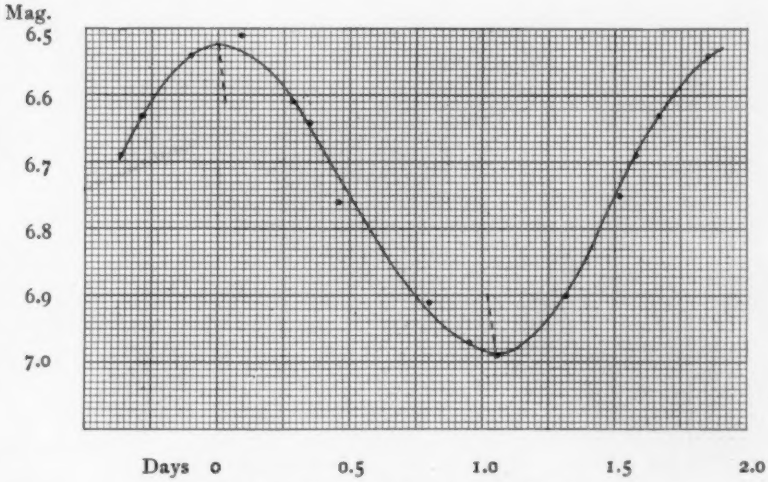
[3] *Astronomical Journal*, **25**, 136, 1907.

[4] *Astronomische Nachrichten*, **177**, 369, 1908.

[5] *Astrophysical Journal*, **26**, 244, 251, 1907.

stars *F* and *D*, making the adopted magnitude of *D* 7.45, which is 0.02 fainter than that adopted in the report on *RZ*.

The extra-focal images were measured with the Hartmann "mikrophotometer" and the magnitudes corrected for atmospheric absorp-



Photographic Light-Curve of *SU Cassiopeiae*

tion and for the position of the star on the plate. The period given in Müller and Kempf's elements of maximum

$$\text{J. D. } 7287.30 + 1^{d}.9498 \text{ E}$$

was found to need a slight negative correction, the observations here given being satisfied by the elements

$$\text{J. D. } 7287.30 + 1^{d}.9490 \text{ E.}$$

With these elements the 86 observations were grouped into 12 normal points given in Table II, from which the mean light-curve shown herewith was drawn. Table I gives in the several columns the current number, the plate number, the Julian day to hundredths in Greenwich mean time, the number of the epoch by the above elements, the phase from the preceding maximum in days, the magnitude, and the residual as found from the curve.

TABLE I

No.	Plate	Julian Day G. M. T.	E	Phase	Mag.	Residual
1	141	7503.56	110	1.87	6.49	−0.05
2		03.57		1.88	6.55	+0.01
3	199	7768.68	246	1.63	6.47	−0.06
4	200	68.82	247	0.12	6.44	−0.10
5		68.84		0.14	6.48	−0.06
6	203	72.65	249	0.05	6.48	−0.04
7		72.67		0.07	6.57	+0.05
8		72.68		0.08	6.56	+0.04
9	207	74.83	250	0.28	6.59	+0.03
10		74.85		0.30	6.57	−0.06
11		76.86	251	0.36	6.68	+0.01
12		90.61	258	0.47	6.75	+0.02
13	210	91.62		1.48	6.79	+0.02
14		91.64		1.50	6.76	0.00
15		91.65		1.51	6.69	−0.06
16		91.66		1.52	6.74	−0.01
17		91.68		1.54	6.67	−0.06
18		91.69		1.55	6.63	−0.09
19		91.70		1.56	6.78	+0.07
20		91.72		1.58	6.62	−0.08
21		91.73		1.59	6.61	+0.02
22		91.74		1.60	6.57	−0.11
23		91.75		1.61	6.59	−0.09
24	213	7821.60	274	0.27	6.66	+0.04
25		21.61		0.28	6.60	−0.02
26		21.62		0.29	6.59	−0.04
27		21.63		0.30	6.63	0.00
28		21.64		0.31	6.55	−0.09
29		21.65		0.32	6.62	−0.02
30		21.66		0.33	6.57	−0.08
31		21.67		0.34	6.59	−0.06
32	214	23.66	275	0.39	6.73	+0.03
33		23.67		0.40	6.73	+0.03
34		23.68		0.41	6.76	−0.06
35	222	30.58	278	1.46	6.75	−0.05
36	224	30.63	278	1.51	6.77	+0.02
37		30.66		1.54	6.81	+0.08
38		30.69		1.57	6.73	+0.03
39		30.72		1.60	6.69	+0.01
40	227	32.60	279	1.53	6.78	+0.04
41	231	32.66		1.59	6.73	+0.04
42		32.67		1.60	6.72	+0.04
43	232	33.70	280	0.68	6.76	−0.09
44		33.71		0.69	6.93	−0.07
45	233	34.73		1.71	6.63	+0.02
46		34.75		1.73	6.60	0.00
47	234	34.77		1.75	6.57	−0.02
48	251	44.57	285	1.81	6.55	−0.02
49		44.59		1.83	6.56	0.00
50	254	49.55	288	0.94	6.92	−0.05
51		49.57		0.96	6.91	−0.06
52	255	49.60		0.99	6.89	−0.09
53	256	51.54	289	0.98	7.05	+0.07
54		51.55		0.99	7.02	+0.04

TABLE I—*Continued*

No.	Plate	Julian Day G. M. T.	E	Phase	Mag.	Residual
55	258	7851.68		1.12	7.02	+0.04
56	262	53.56	290	1.05	7.01	+0.02
57		53.57		1.06	7.07	+0.08
58	265	54.57	291	0.11	6.47	−0.05
59		54.58		0.12	6.53	0.00
60	268	55.54		1.08	6.96	−0.03
61		55.56		1.10	6.99	+0.01
62		55.65		1.19	6.98	+0.02
63	272	56.89	292	0.48	6.75	0.00
64		56.90		0.49	6.81	+0.05
65	276	59.57	293	1.21	7.03	+0.08
66		59.62		1.26	6.98	+0.04
67	279	59.70		1.34	6.87	−0.02
68		59.76		1.40	6.93	+0.08
69	284	82.67	305	0.93	6.99	+0.03
70	286	83.55		1.81	6.55	−0.02
71		83.56		1.82	6.49	−0.07
73		83.57		1.83	6.62	+0.06
74	288	84.53	306	0.84	6.99	+0.07
75		84.54		0.85	6.90	−0.03
76	288	84.58	306	0.89	6.92	+0.03
77	291	86.51	307	0.87	6.97	+0.03
78		86.52		0.88	6.86	+0.07
79		86.56		0.92	6.92	−0.04
80		86.57		0.94	6.95	−0.02
81	293	86.60		0.96	7.06	+0.09
82	300	91.55	361	0.66	6.89	+0.04
83	302	91.61		0.72	6.85	−0.02
84	303	99.55	365	0.87	6.96	+0.01
85		7999.56		0.88	6.95	0.00
86	306	8037.59	384	1.87	6.56	+0.02

TABLE II

NORMAL POINTS FOR MEAN CURVE

Phase	Mag.	No.
d	M	
0.09	6.51	7
0.29	6.61	6
0.35	6.64	7
0.46	6.76	5
0.80	6.91	11
0.95	6.97	7
1.06	6.99	7
1.32	6.90	7
1.52	6.75	7
1.58	6.69	7
1.67	6.63	6
1.85	6.54	9

In the reductions, as explained in the article last cited, the mean of the photometer scale-readings for the stars F and D were taken as corresponding to the mean of the adopted magnitudes, 6.80, and the magnitudes of the standards and the variable stars were found by the use of the "absolute scale." If this scale had been corrected for each plate so as to make the interval between the standards 1.30 magnitudes in each case, the residuals given in the last column of Table I would be reduced to a slight extent; and such a procedure would be quite justified. But it was thought best in this case to use the uncorrected scale so as to show the capability of the "absolute scale" to represent magnitudes on a series of plates taken at different times and separately developed. The sources of error included in the residuals, in their estimated order of importance, are:

1. Local errors on the plate, due to lack of uniformity in the thickness of the sensitive film. In exceptional cases these might be as large as a quarter of a magnitude, but on these plates (24 on commercial, 12 on plate glass) they do not seem to have exceeded one- or two-tenths of a magnitude.

2. Differences in the gradation of the plate due to some peculiarity in the manufacture or development. The latter was kept as uniform as possible in agent, time, and temperature.

3. Errors in measurement of the plates. Judging by the mutual agreement of the photometer settings these were quite small. Three settings were made on each star-disc and if the range exceeded 0.02 magnitude, additional settings were made.

4. Errors in the adopted absorption curve of the photometer wedge. As this curve depends on several thousand settings on a large number of sensitometer plates, the errors are supposed to be small.

The combined effect of these causes is such as to make the calculated probable error of a single observed magnitude ± 0.033.

The resulting mean light-curve shows a continuous variation with range of 0.47 from 6.52 to 6.99 magnitudes. The time from minimum to maximum is 0.90 day, or 46 per cent. of the period; therefore the rise is slightly faster than the decline.

As the visual magnitudes cited at the beginning of this paper are all based on 6.15 for the star F, the differences between visual and

photographic magnitudes give directly the color-intensity. The respective ranges are:

	Maximum	Minimum
Müller and Kempf..........	5.93	6.26
Von Zeipel..................	5.92	6.32
Photographic...............	6.52	6.99

The color-intensities are therefore 0.59 or 0.60 at maximum and 0.73 or 0.67 at minimum, from Müller and Kempf and von Zeipel respectively. The best objective-prism plates show the spectrum of *SU* to be F 3 G in the system described by Jordan and the writer,[1] calling for a color-intensity of 0.62 at phase $1^{d}.28$. This agreement is very satisfactory.

The radial velocity of this star has been measured on nine plates taken with the Bruce spectrograph on the 40-inch refractor. On account of the faintness of the star only one prism could be used and four hours' exposure was required, so that no great accuracy could be expected in the results. The total range observed is from -1 to -16 km, but the data are insufficient to determine whether this range is real or whether it bears any relation to the cycle of light-change. More plates will be taken when the star comes again into position.

YERKES OBSERVATORY
May 1908

[1] "The Photographic Determination of Star-Colors and Their Relation to Spectral Type," *Astrophysical Journal*, **27**, 169, 1908.

THE REPRODUCTION OF PRISMATIC SPECTRUM PHOTOGRAPHS ON A UNIFORM SCALE OF WAVE-LENGTHS

By A. FOWLER and A. EAGLE

In the course of spectroscopic work it is sometimes useful to be able to make direct comparisons of photographs taken by the use of prisms with those obtained by means of gratings. For this purpose, owing to the varying dispersion of prisms, it is necessary to reproduce the prismatic spectrum on a uniform scale of wave-lengths corresponding to that of the grating photograph with which the comparison is desired.

The method of rectifying the prismatic spectrum which is here described was arrived at quite independently, but it has been found since that the same general procedure was suggested and applied by E. S. King in 1898.[1] In both cases the original negative is placed in front of the copying camera in an inclined position with the less refrangible end nearer the lens, and the plate or bromide paper on which the image is received is also inclined at an angle to suit the particular case.

Mr. King appears to have obtained his angles and distances by trial—by adjusting until three lines in the spectrum were on the desired normal scale. He did not so far as we know give general formulae which make the method readily applicable to particular cases, and it may be of interest to indicate how these are derived, especially as it can be shown that the method gives a more accurate normalization than might have been anticipated.

The adjustment by trial is moreover rather troublesome and unsatisfactory. Four things have to be varied, viz., two distances and two angles so as to satisfy three conditions simultaneously: (1) a normal spectrum, (2) the desired scale, and (3) good focus throughout.

The best approximation to the dispersion curve of a prismatic

[1] Report of the Harvard Astrophysical Conference, *Science*, **8**, 454, 1898.

spectrum which has yet been found is that given by the well-known Cornu-Hartmann formula:

$$\lambda=\lambda_0+\frac{c}{s-s_0}.$$

where c, λ_0, and s_0 are constants, and λ is the wave-length corresponding to the scale-reading s. Practical experience has shown that this equation holds very closely over a long range of the spectrum, and the following analysis indicates that the accuracy with which a prismatic spectrum can be reduced to a normal one is equal to that with which it may be represented by the above equation.

Let L be a lens which will bring equidistant points lying on a plane AB perpendicular to the axis of the lens, into focus as a system of equidistant images on another plane CD.

Then we can show that points lying on an inclined plane PS will be brought into focus on another plane QT.

In the diagram let $EL=u$, $FL=v$, $PG=x$, $PH=y$, $QJ=X$, $QK=Y$, $\angle SEB=\phi$, and $\angle QFD=\psi$.

Treating the lens as a thin lens, we have $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$, where f is the focal length. Hence, Q being the image of P,

$$\frac{1}{PM}+\frac{1}{QN}=\frac{1}{f},$$

where M and N are the feet of the perpendiculars from P and Q to the plane containing the lens. Hence

$$\frac{1}{u-y}+\frac{1}{v+Y}=\frac{1}{f},$$

or

$$v+Y=\frac{f(u-y)}{u-y-f}: \qquad (1)$$

subtracting $v=\frac{fu}{u-f}$ from each side we have

$$Y=\frac{yf^2}{(u-f)(u-f-y)}. \qquad (2)$$

Also

$$\frac{X}{x}=\frac{LJ}{LG}=\frac{v+Y}{u-y}.$$

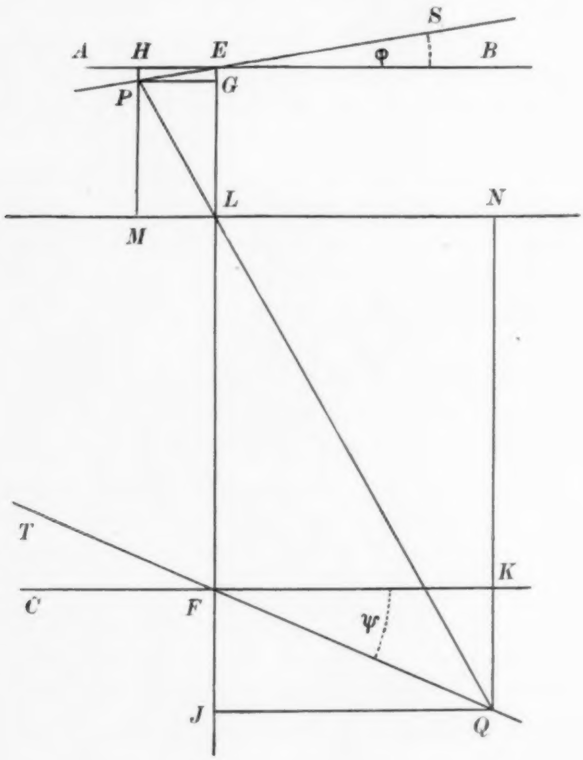
Using (1) we have

$$\frac{X}{x}=\frac{f}{u-f-y}; \qquad (3)$$

combining (2) and (3) we obtain

$$\frac{Y}{X}=\frac{y}{x}\frac{f}{u-f}=\frac{y}{x}\frac{v}{u}, \tag{4}$$

or, since $\frac{y}{x}$ is constant along PS we see that $\frac{Y}{X}$ will be constant. That is, all points lying on PS will be brought into focus on another straight line QT.



Equation (4) may be written

$$\tan\psi=\frac{v}{u}\tan\phi.$$

We require now to find how the dispersion varies along QT. Let $PE^2=s^2\equiv x^2+y^2$ and $QF^2=l^2\equiv X^2+Y^2$.

Then

$$l^2=\frac{f^2}{(u-f-y)^2}\left\{x^2+\frac{y^2f^2}{(u-f)^2}\right\}$$

from (2) and (3); or, putting $x=s\cos\phi$ and $y=s\sin\phi$

$$l=\frac{fs}{u-f-s\sin\phi}\sqrt{\cos^2\phi+\frac{v^2}{u^2}\sin^2\phi}\,.$$

For brevity write K^2 for the quantity under the radical sign, which is a constant with respect to s.

Then

$$l=\frac{fKs}{u-f-s\sin\phi}\,.$$

Hence

$$\frac{dl}{ds}=\frac{fK(u-f)}{(u-f-s\sin\phi)^2}\,.$$

Now if we have a prismatic spectrum on the plate PS for which the wave-length at the distance s from the center of the plate is given by

$$\lambda=\lambda_0+\frac{c}{s-s_0}\,,$$

we have

$$\frac{d\lambda}{ds}=\frac{-c}{(s-s_0)^2}\,.$$

Hence for the spectrum on QT we shall have

$$\frac{d\lambda}{dl}=\frac{d\lambda}{ds}\frac{ds}{dl}=\frac{c(u-f-s\sin\phi)^2}{fK(u-f)(s-s_0)^2}\,.$$

If now we can make $u-f-s\sin\phi$ always proportional to s_0-s, we see that $\frac{d\lambda}{dl}$ will be a constant independent of s; that is, the spectrum will be normal.

The condition for this to be so is evidently

$$u-f=s_0\sin\phi\,. \qquad (5)$$

When this holds

$$\frac{d\lambda}{dl}=\frac{c\sin^2\phi}{Kf(u-f)}=\frac{c\sin\phi}{fKs_0}\,. \qquad (6)$$

Now the value of $\frac{d\lambda}{dl}$ is known; it is the number of tenth-meters per centimeter we require in the normal spectrum. Let this be N.

Then from (6), on replacing K by its proper value—which may be written

$$\sqrt{\cos^2\phi+\frac{f^2\sin^2\phi}{(u-f)^2}} \text{ or } \sqrt{\cos^2\phi+\frac{f^2}{s_0^2}}$$

we have

$$N^2f^2(s_0^2\cos^2\phi+f^2)=c^2\sin^2\phi\,.$$

Hence

$$\sin\phi=\frac{Nf\sqrt{s_0^2+f^2}}{\sqrt{c^2+N^2f^2s_0^2}}\,. \tag{7}$$

Sin ϕ having been found from this equation the distance u is found from (5) and v is given by

$$v=\frac{fu}{f-u}=\frac{fu}{s_0\sin\phi}\,.$$

Lastly, the angle ψ is determined from the equation

$$\tan\psi=\frac{v}{u}\tan\phi=\frac{f}{s_0\sin\phi}\tan\phi=\frac{f}{s_0\cos\phi}\,. \tag{8}$$

From (5) and (8) we have

$$u+v=u+\frac{fu}{s_0\sin\phi}=\frac{(f+s_0\sin\phi)^2}{s_0\sin\phi}\,. \tag{9}$$

Equations (7), (8), and (9) give all the data required, viz., ϕ, ψ, and $u+v$.

We have found it convenient for the practical application of the process to replace the copying-board of the usual enlarging apparatus by one pivoted at the middle and provided at the back with a circular slot and clamp screw, a millimeter scale being let into the base so that its reading at once gives tan ψ. The swing-back of the camera which holds the negative readily permits adjustment of the angle ϕ. In practice the angles ϕ and ψ were set to their calculated values, as also was the total distance $u+v$ between the negative and the copying board. The focusing was done by moving the camera lens with

the rack. When the enlargement is required to fit exactly some given scale or spectrum, the position of the lens is adjusted until this scale is exactly obtained in the image.

If the negative has been measured for the determination of wave-lengths, the constants of the Cornu-Hartmann formula will already have been obtained for it. It is necessary, however, to replace the constant s_0 obtained in the usual way by the value of $s-s_0$ for the center of the plate. This is of course the change introduced when s is measured from the center.

The following is an example showing the accuracy obtained. The equation of the prismatic spectrum obtained in the ordinary way—s being expressed in inches—is

$$\lambda=2566.60+\frac{50{,}951}{23.956-s}.$$

In this equation the scale reading of the line $\lambda=4859.93$ is 1.730. This line was 1.17 inches from the center of the plate so that the scale reading at the center was 2.90. Accordingly when s is measured from the center as origin, the equation becomes

$$\lambda=2566.6+\frac{50{,}951}{21.046-s'}.$$

On taking $N=30$ so as to obtain a normal spectrum on a scale of 30 tenth-meters to the inch, and taking the focal length of the lens as 5.93 inches, we find for this equation, by means of the previous formulae,

$$\tan\phi=0.076$$
$$\tan\psi=0.283$$
$$u+v=35.5 \text{ in.}$$

The negative was placed in the camera so that the center of the plate was on the axis of the lens. The enlargement was made on a plate which was measured afterward, and, a line near each end of the plate being taken as a standard, the wave-lengths of the intermediate lines were calculated by a linear interpolation formula. The figures indicate the results obtained for a portion of the iron arc.

λ observed	s (inches)	λ calculated	O.—C.
4823.697	.000	....	......
59.928	1.2095	.936	−.008
78.407	1.8248	.375	+.032
4903.502	2.6630	.490	+.012
24.956	3.3795	.960	−.004
34.245	3.6905	.279	−.034
46.568	4.1032	.642	−.074
66.270	4.7606	.343	−.073
94.316	5.6980	.431	−.115
5028.308	6.8315	.394	−.086
51.825	7.6153	.881	−.056
83.518	8.6728	.567	−.049
5110.574	9.5748	.593	−.019
27.533	10.1401	....	......

Thus, the greatest error in wave-length in a range of over 10 inches is about 0.1 tenth-meter. This corresponds to a displacement of a line of about $\frac{1}{300}$ of an inch. If half the range had been taken, the error would only have been one-quarter of this amount. Had our apparatus enabled us to set the angles more accurately, the errors could perhaps have been rendered still smaller than the above. The scale of the enlargement between the two extreme lines corresponds to 29.964 tenth-meters to the inch. The focusing was adjusted to give what appeared to be the best definition and not to give the exact scale, but the agreement is probably closer than could generally be expected. The same method has also been applied successfully to the production of normal frequency spectra.

If it be desired to compare two prismatic spectra which have different values of λ_0 they may both be reproduced as normal spectra on the same scale.

If the formulae be applied to normalize a prismatic spectrum which is on too small a scale, it will be found that the angles become too great to be practicable. This difficulty can, however, always be overcome by making intermediate ordinary enlargements in sections and then normalizing each section. It is not practicable to have $\tan\psi$ much greater than 0.5. This means that $s_0 \cos\phi > 2f$ by (8), or, since $\cos\phi$ is approximately unity, we have $s_0 > 2f$. This condition will at once enable us to see if the method is practicable in any given case.

When on the contrary the angles are small, simpler expressions may be found for them. In this case

$$\sin \phi = \frac{N f s_o}{c},$$

and

$$\tan \psi = \frac{f}{s_o}.$$

The expression for $\sin \phi$ may be still further simplified. If λ_m is the wave-length at the center of the plate, i. e., corresponding to $s=0$, we have $(\lambda_m - \lambda_o)s_o = c$. Hence

$$\sin \phi = \frac{N f}{\lambda_m - \lambda_o}.$$

It will be seen that the angles are smaller, the smaller the focal length of the lens. We have found a lens of 6 in. focal length to work admirably in enlarging 3 or 4 in. of an original negative into a strip 15 in. long of a normal spectrum covering about 190 tenth-meters.

The focal length of the lens should be known fairly accurately, and a convenient way of finding it is to put a negative in the camera and focus it on the copying board in the usual manner. Then if d is the distance between two lines on the negative, d' the distance between their images, and l the distance from the negative to the copying board the focal length is given by

$$f = \frac{l d d'}{(d+d')^2}.$$

Imperial College of Science and Technology
London
July 1908

COMET *c* 1908 (MOREHOUSE)

By E. E. BARNARD

Though comparatively faint and quiet in the visual telescope, this comet has shown extraordinary activity from a photographic standpoint. It is fair to say that no other comet has approached it in interest and importance since photography has been applied to these bodies. One remarkable advantage in its study has been the high northern declination of the comet, which for a time permitted exposures throughout the night. Advantage was taken of this fact to make series of photographs at intervals of one or two hours on several dates. By this means the complete history of some of the changes has been secured, so that it is possible to say just how this or that change took place. Some of the pictures show all these various stages of change.

The general tendency of the comet has been to produce a tail by a steady outflow of various streams of matter, but on several occasions great masses were thrown off which could be followed outward from the comet for several days before they finally dissipated into space. In some cases these masses were sufficiently dense to throw off streams or tails independently, in a similar manner to the parent comet. Very much material exists in these photographs for determining the motion of these masses, and when these are compared with photographs made elsewhere the entire motion of a mass from its original ejection until it melted away should be determinate.

The greatest changes in the comet, so far as covered by my photographs, occurred on September 30, October 1, and October 15. Those of September 30 and October 1 are the most interesting because of the beautiful and unique aspect of the comet during part of the time on September 30. The two plates (XXI and XXII) that accompany this paper give a good idea as to how the comet may utterly transform itself in a few hours.

The most remarkable transformation occurred on September 30 and October 1. It began between the 29th and 30th of September

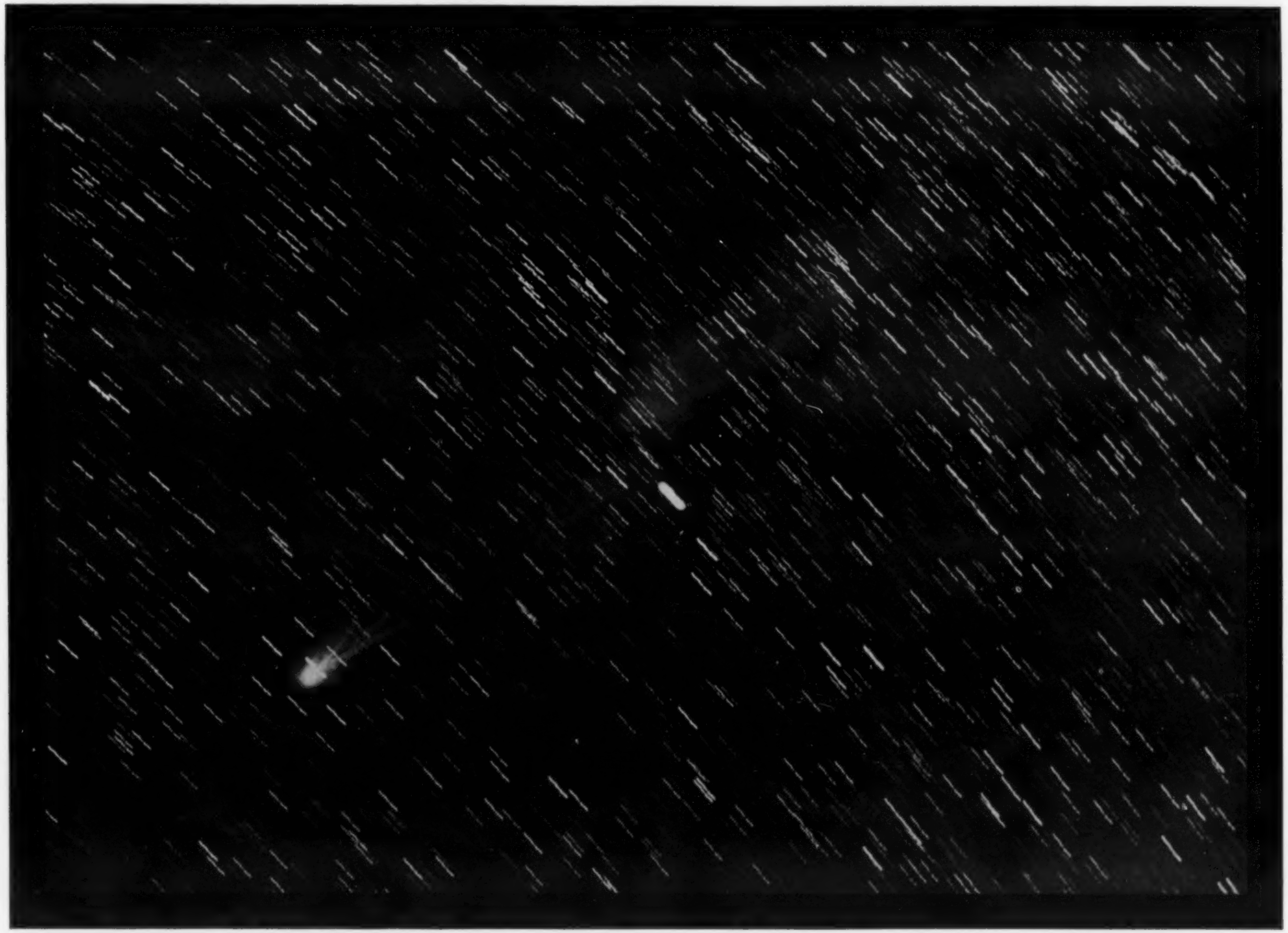
PLATE XXI

South

COMET 1908 *c* (MOREHOUSE) ON SEPTEMBER 30, 1908, AT $14^h\ 22^m$ C. S. T. EXPOSURE $1^h\ 56^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm=0°.36

PLATE XXII

South



Comet 1908 *c* (Morehouse) on October 1, 1908, at $13^h\ 43^m$ C. S. T. Exposure $2^h\ 0^m$

10-Inch Lens of Bruce Telescope. Scale: 1cm=0°.36

and ended October 1. On September 30 a violent change was taking place throughout the night. Each exposure, separated by a couple of hours, showed a great variation in the comet. The last exposure on this date closed at $21^h 20^m$ Greenwich M. T. The first exposure on October 1 began at $13^h 9^m$. There is therefore an interval of about 16^h between these two pictures during which time the most remarkable part of the transformation must have taken place. If any photographs were made in England or on the continent during this time, they will be of the utmost importance in showing the process of the complete transformation of the comet on the dates specified. Any such photographs should be published—or at least their existence should be made known.

I have one photograph on September 29, $10^h 45^m$, with an exposure of $2^h 30^m$ through breaks in clouds. This shows a disturbed condition of the comet which possibly was the forerunner of the great change that followed in the next two days.

September 30. The first exposure was not especially remarkable. The head was rather small. From this a rather thick tail ran out in a straggling manner with a fainter sheeting of matter having a sharp edge on the south side. In the next picture the whole tail had moved out bodily and was connected with the head by a very narrow, tapering neck. The tail was wide and larger, widening out very greatly as it left the head. The northern part of the tail was the brightest and was greatly curved. Fluffy masses projected from the north side of this. In the third picture the comet had become a very remarkable and beautiful object, utterly different from the first picture. The tail had tapered down to a very narrow connection with the head which was very small and almost starlike. The fluffy masses had become a large projection from the north side of the tail. The appearance of the comet in this plate is unique and very beautiful. The tail appears cyclonic in form and structure. Doubtless an hour or so later the whole tail had become disconnected from the head, as the separation is essentially shown on the last plate. Such a complete separation of the tail from the head is actually shown in a photograph on September 20. It is really impossible properly to describe the remarkable transformation of the comet on this date. It is to be regretted that another picture was not made between the last one and daylight,

but instead the time until $16\frac{1}{2}$ hours was devoted to an exposure in another part of the sky.

The first of the pictures on October 1 showed, about 2° out from the comet, what was evidently the great mass of matter that formed the tail of September 30. The tail was almost 8° long. The outer 6° of this was made up of an irregular, long, straggling mass which had a tendency to spread northward. This great mass was apparently attached to the head of the comet by a slender thread, alongside of which to the south was another threadlike stream which, though connected with the mass, does not appear to quite reach the comet. There is a narrow, short ray from the head, at an angle of 45° with the tail on the south side.

In the second plate two rays connect with the great mass, one of which, after running parallel with the main one for a degree, bends in and joins it, making only one ray that reaches the head.

In the third plate there is a great change. A diffused ray has shot out from the head for a degree on the north side, while there are several streamers connecting the mass with the head. The fourth shows still greater changes. The new ray about a degree away merges into the straggling rays from the head to the mass. In the fifth, the new ray curves northward and then joins the system of rays from the head at a distance of 2°. In this plate the outward end of the ray system has become disconnected from the great mass, which has become square in form and more sharply defined at its end toward the head. In the sixth picture the separation is complete and the end of the great mass is more pointed.

On October 2 the comet had a changing system of broad curving streamers spreading out at wide angles. On October 3 the tail consisted of a widely diverging skeleton framework changing rather slowly and becoming rather complicated with new streams which in the last picture of that date were diffusing as if to join in making an ordinary tail, such as it had on the following night, October 4.

On October 15 another great disturbance occurred. The first photograph shows a straight narrow tail extending for half a degree with a short ray from each side of the head at angles of about 30° and 45°. At the end of the narrow tail $\frac{1}{2}$° from the head begins a most extraordinary tail which is twisted and clouded at the begin-

ning and which streams irregularly away, bending northward in irregular outline for 7° or 8° to the edge of the plate. In this first picture the straight tail joins the south portion of this twisted mass; and in the last picture of this date it makes a juncture farther north at about the middle of the mass which is $\frac{1}{4}$° broad where it begins. These masses are very dense and from the south part narrow streamers run out parallel with the short tail for about 2°. In the photographs of October 14 there were no indications of this disturbance. Remnants of these cloud masses, however, are shown much farther out in the photographs of October 16 and 17.

On October 15, after making the second exposure for that night, I developed my plates to see if the comet was in any way abnormal. As soon as I saw the remarkable appearance of the tail I at once began a new set of exposures and carried the comet as long as I could follow it in the haze and moonlight. There is therefore a good record of the part of this disturbance that was visible here.

There seems to have been a similar disturbance on October 6, as the photograph taken on that date shows a straight, narrow tail connected at its end with large cloudlike masses.

A very great change in the condition and direction of the tail occurred about September 16. A photograph on that date, through a very thick sky, showed the tail violently curved at a large angle to its normal direction and to the position it had later on September 17.

This comet has forcibly impressed upon us the necessity of testing all comets photographically with a reasonable exposure once or twice during their visibility to see if they are active. I have done this, in a sense, with a number of these bodies, but have essentially found that a comet when faint, like this one at first, does not seem to show evidences of activity or of a tail. Such exposures have usually resulted in adding nothing to the telescopic view. The present comet, had its discovery been a visual one, would not have suggested any promising results from the application of photography, because it was faint visually, and apparently without any or with but little tail. The discovery photograph (made by Professor Morehouse) showed, however, that the comet was really a very active one. This led to its being followed faithfully with the photographic plate. It is indeed remarkable how strongly photographic this comet has proved to be. Until recently it

has been a rather faint object in the 5-inch guiding telescope of the Bruce, especially so when the guiding wires, with the smallest possible illumination, have been placed over it; yet at the same time that portion which could be seen at all, readily photographed in a few minutes, and a longer exposure brought out features that could never have been suspected visually.

One fact that is specially emphasized by these pictures with the different lenses is, that what we might, with a long exposure, take to be a picture of the comet may be only a composite made up of the various forms it has assumed during the exposure. In one or more cases the exposure with the 3-inch lens has been carried forward over several exposures with the other lenses. The result is a considerably different looking comet in the several pictures. Of course this is not so true when the comet is changing slowly.

As is known, the Bruce telescope of the Yerkes Observatory consists of two portrait lenses of 10 and $6\frac{1}{4}$ inches aperture. These are bound rigidly together along with a 5-inch guiding telescope. There is also attached to it, in a wooden box, a third lens of $3\frac{4}{10}$ inches diameter. All three lenses have been used in the work on the comet with great success. The smaller lens, while showing practically everything obtained with the larger ones but on a smaller scale, gave the full extent of the tail, which sometimes extended beyond the edges of the larger plates.

For the benefit of those interested in the comet the following table contains a list of the photographs which I have thus far secured. It has been photographed on every possible occasion, and will be followed as long as photographs can be made of it from this latitude.

The short exposures have been through breaks in clouds or in moonlight. Altogether about 190 negatives have been made of the comet with the three lenses.

There will be a great deal of material in these photographs, and in others taken elsewhere, for determining the motion of the particles of the tail. It is very evident, however, that this must be used with great caution or it may lead to erroneous conclusions. The very conditions favorable for determining the motion, i. e., definite masses receding from the comet, are apparently adverse to a determination of the true motion of the average particles whose outward

Central Standard Time	10-Inch		6-Inch		3.4-Inch	
	Middle of Exposure	Duration	Middle of Exposure	Duration	Middle of Exposure	Duration
1908						
Sept. 2......	11^h 42^m	2^h 0^m	11^h 42^m	2^h 0^m	11^h 42^m	2^h 0^m
3......	13 35	3 45	13 35	3 45	13 35	3 45
3......	16 4	0 22	16 4	0 22		
5......	14 47	2 46	14 47	2 46		
6......	14 44	2 40	14 44	2 40	14 44	2 40
7......	15 14	1 48	15 14	1 48	15 14	1 48
8......	16 6	2 3	16 6	2 3	16 6	2 3
12......			8 4	0 18		
16......	9 35	1 55	9 35	1 55	9 35	1 55
17......	10 15	2 30	10 15	2 30		
18	9 37	3 17	9 37	3 17	9 37	3 17
19......	9 51	4 7	9 51	4 7	9 51	4 7
20......	12 38	1 6	12 38	1 6		
21......	11 16	3 37	10 28	2 0	11 21	3 47
21......			12 20	1 30		
21......	14 25	1 40	14 25	1 40	14 25	1 40
23......	9 58	3 32	9 7	1 50	9 24	2 25
23......			11 2	1 25		
24......			8 0	0 55	8 0	0 55
25......	9 6	4 7	8 2	2 0	9 6	4 7
25......			10 9	2 0		
25.	13 43	2 18	13 43	2 18		
26......	9 3	4 12	7 57	2 0	9 0	4 0
26......	12 14	1 25	12 14	1 25		
29......	10 40	2 20	10 45	2 30	10 40	2 20
30......	11 46	3 0	11 16	2 0	12 48	5 4
30......	14 22	1 56	13 25	2 0		
30......			14 57	0 47		
Oct. 1......	9 7	4 0	7 37	1 0	8 7	2 0
1......	11 21	2 7	8 43	0 50	13 43	2 5
1......	13 43	2 0	10 48	1 0		
1......			11 55	1 0		
1......			13 15	1 5		
1......			15 0	0 35		
2......	10 51	1 5	7 29	1 2	7 29	1 2
2......	12 28	2 0	10 3	1 30	10 23	2 10
2......	14 59	2 49	11 38	1 30	12 38	2 10
2......			13 16	1 30	15 1	2 46
2......			15 18	2 11		
3......	8 14	1 14	8 11	1 19	11 27	3 8
3......	11 7	2 28	10 45	1 45	11 29	3 8
3......	13 35	2 21	12 43	1 54	14 58	3 35
3......	15 48	1 47	14 38	1 30		
3......			16 8	1 7		
4......	13 5	1 45	13 5	1 45	13 5	1 45
5......	13 40	1 40	13 35	1 35	14 15	2 50
5......	15 37	2 6	15 31	2 18	15 35	2 20
6......	15 58	1 24	15 58	1 24	15 58	1 24
7......	16 10	1 1	16 10	1 1	16 10	1 1
8......	8 2	0 30	8 2	0 30	8 2	0 30
9......	6 43	0 37	6 43	0 37	6 43	0 37
11......	6 42	0 35	6 42	0 35	6 42	0 35
12......	6 50	1 9	6 50	1 9	6 50	1 9

Central Standard Time	10-Inch		6-Inch		3.4-Inch	
	Middle of Exposure	Duration	Middle of Exposure	Duration	Middle of Exposure	Duration
1908						
Oct. 12......	9^h 27^m	0^h 30^m	9^h 27^m	0^h 30^m	9^h 27^m	0^h 30^m
13......	6 50	1 1	6 50	1 1	6 50	1 1
14......	6 52	1 5	6 50	1 0	6 59	1 10
14......	8 4	1 10	8 1	1 15	8 9	1 0
15......	6 58	1 22	6 54	1 15	7 35	2 36
15......	8 31	1 30	8 30	1 33	9 14	0 30
15......	10 58	0 57	10 54	0 49	11 29	2 0
15......	12 2	0 54	12 12	0 54		
15......	13 11	0 33	13 11	0 33		
16......	6 54	1 20	6 54	1 20	6 54	1 20
16......	9 32	2 15	9 32	2 15	9 32	2 15
17......	6 38	0 47	6 38	0 47	6 38	0 47
17......	8 2	0 10	8 2	0 10	10 41	2 10
17......	10 38	2 5	10 38	2 5		
19......	8 38	1 30	8 38	1 30	8 38	1 30
21......	7 10	1 56	7 10	1 56	7 20	2 10
21......	9 19	2 3	9 19	2 3	9 19	2 3
22......	8 2	0 35	8 2	0 35	8 2	0 35
24......	10 33	0 18	10 33	0 18	10 33	0 18

flow forms the tail. It would seem reasonable that these masses would have a much slower speed than the individual particles forming the general stream of the tail. They probably contain particles of greater size and mass which would be less under the influence of the pressure of sunlight, and would, therefore, have a much less outward velocity than the general particles of the tail. Whatever the cause, the fact is that on several occasions these masses have had independent streams or tails issuing from them, like those from the comet itself, where the smaller particles are evidently detached from the mass and forced out with a very much greater velocity. This was also shown in the case of Daniel's comet on July 11, 1907, where a mass left behind was actually moving sunward under the combined influence of gravitation and the initial velocity of its particles when component parts of the head. I have called attention to this peculiarity in the case of Borrelley's comet, where the new tail on July 24, 1903, was moving out more rapidly than the rear portion of the old disconnected tail, which was at that time drifting away from the comet and the sun (*Astrophysical Journal*, **18,** 211, 1903).

An example of secondary tails from receding masses is found on a photograph of Swift's comet on April 7, 1892. (See *Popular Astron-*

omy, **12**, 2, 1904. for a photograph and description of the comet on this date.) Morehouse's comet also presented a similar appearance on October 15.

In a paper "On the Anomalous Tails of Comets" (*Astrophysical Journal*, **22**, 249, 1905) I urged the necessity of employing shorter intervals than a day, to photographically connect the physical changes occurring in an active comet. It was shown that a history from hour to hour was necessary to correctly represent the progress of these changes, for a comet would at times completely transform itself in a day. In that paper attention was also called to the opportunity offered by a comet at a high northern declination for repeated exposures throughout the night. These facts have been more clearly brought out by the present comet. The photographs of it have proved the extraordinary rapidity with which a comet can alter its appearance when in one of its changing moods.

Yerkes Observatory
October 26, 1908

AN ELECTRIC FURNACE FOR SPECTROSCOPIC INVESTIGATIONS, WITH RESULTS FOR THE SPECTRA OF TITANIUM AND VANADIUM[1]

By ARTHUR S. KING

In designing an electric furnace for spectroscopic work in the laboratory of the Mount Wilson Solar Observatory, several requirements were kept in mind.

1. An apparatus which should give a long, uniformly heated column of vapor which might be brought to a temperature not very much below that of the electric arc. This need was shown by preliminary experiments which demonstrated the difficulty of producing by furnace methods the spectra of refractory substances such as titanium and vanadium, highly important in solar investigations.

2. Regulation of the furnace temperature, so that the direct effect of varying temperature might be observed, when other conditions remained unchanged.

3. The control of the conditions surrounding the luminous vapor, to observe the effect of changes in pressure and surrounding atmosphere. If spectra can be produced giving almost as many lines as the arc, the superiority of the furnace is manifest in that the effect of external influences such as pressure may be observed without an accompanying change in the action of the light-source itself, such as must take place in the arc or spark under pressure.

4. The possibility to observe absorption effects given when white light is passed through the highly heated vapor in the furnace.

The development of electric furnace work has shown that the type known as the "tube resistance furnace" is the one best adapted to all of these requirements. The temperature in such a furnace is regulated by the strength of the current passing through a tube, usually of carbon or graphite, supported horizontally and containing the substance to be vaporized. Such a tube must of course be pro-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28.

PLATE XXIII

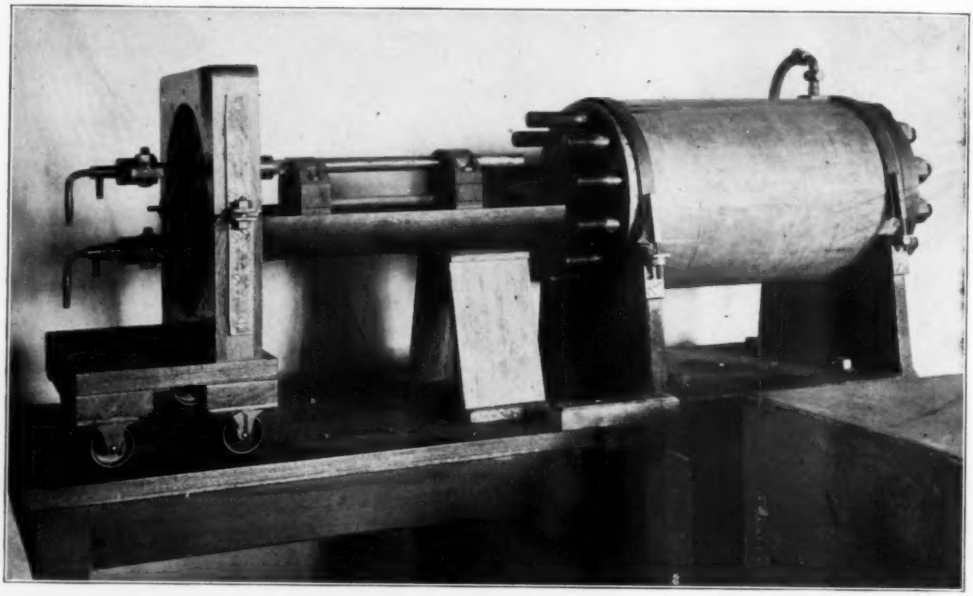


FIG. 1.—ELECTRIC FURNACE OPEN, WITH JACKETING MATERIAL REMOVED

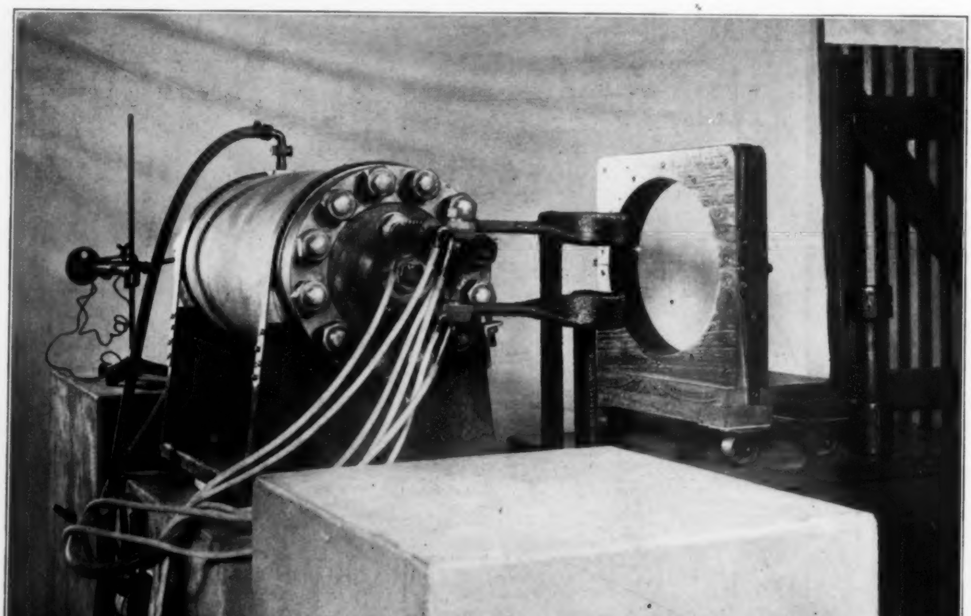


FIG. 2.—ELECTRIC FURNACE CLOSED, IN POSITION

tected from contact with the air, which would cause it to be quickly consumed. The best protection has been found to be a vacuum or a neutral gas around the tube. The inclosure in which the tube is placed for this purpose may be made strong enough to withstand any desired pressure. Such an apparatus, with a regulated current supply to the tube and windows in the walls of the chamber through which the interior of the tube could be observed, would fulfil the several purposes already outlined.

The furnace will be only briefly described in this paper, with a short account of its performance in the first investigation undertaken. The complete description, with detailed drawings, and the full discussion of the results with their bearing on astrophysical problems will be left for a later paper in the *Publications* of the Solar Observatory.

Plan of furnace.—The method adopted for the construction of the furnace was to arrange all of the essential parts in the form of a cartridge attached to one of the heads of a steel chamber, this chamber being built to stand high pressures. The arrangement is clearly shown in the photograph of the open furnace (Plate XXIII, Fig. 1). A half-cylinder of iron, screwed firmly to the head of the pressure chamber, contains two graphite blocks which serve to hold the ends of the horizontal resistance tube and also establish contact between these ends and the copper pipe electrodes which pass through the steel head and carry the electric current. These graphite blocks are each 2 inches thick, about 6 inches wide at the middle, and in three sections. The block for the lower electrode has its top cut low enough to allow the passage of the upper electrode. The blocks are provided with vertical bolts $\frac{3}{8}$ inch in diameter, which hold the sections of the block together and when tightened make firm contact between the copper electrodes and the ends of the resistance tube. Sheets of asbestos or mica under the blocks secure insulation from the iron half-cylinder.

The length of the upper electrode at present employed permits the use of resistance tubes 16 inches long, with 9 inches to be heated between the blocks. Shorter tubes may of course be used by placing the blocks closer together, as contact can be made at any point along the upper electrode. With a longer pipe above, the size of the

inclosing chamber would permit the use of a resistance tube about 22 inches long, with 18 inches heated.

The jacketing about the resistance tube for heat insulation is not shown in the photograph. It was found, as has been noted by other workers in this field, that any jacketing material placed in contact with the resistance tube will fuse to some extent and conduct part of the current. The jacketing now in use works well. A carbon tube was made by boring out a rectangular block (round would serve as well) from end to end with a hole $\frac{1}{4}$ inch larger than the resistance tube to be used. The length was $\frac{1}{2}$ inch less than that of the resistance tube between blocks, the walls no thicker than necessary to secure strength. This tube was split from end to end so that it could be placed around the resistance tube after the latter was in position, giving a free space of about $\frac{1}{8}$ inch all around the resistance tube. The space between this carbon protector and the iron half-cylinder was then filled with carborundum powder, a complete jacketing being obtained by heaping the carborundum entirely over the carbon protector, stiff sheets of mica at the sides of the iron half-cylinder enabling this to be done.

Electrodes.—The current is carried to the ends of the resistance tube by two copper pipes passing through the cylinder head in insulated bushings. Each pipe is made of two tubes, one inside the other, of $\frac{1}{2}$ inch and $\frac{3}{4}$ inch iron pipe size respectively, giving a tube of $\frac{5}{8}$ inch I. D. and $1\frac{1}{16}$ inch O. D. This pipe is plugged at the inner end and the water cooling is given by a thin-walled copper tube, supported coaxial with the electrode pipe, carrying water to one inch from the end of the latter, the water then flowing back and bathing the inner wall of the electrode. A heavy copper lug connects the copper pipe outside the cylinder head to a copper bar $\frac{1}{2} \times 2\frac{1}{2}$ inches which passes to the terminals of the cable from the transformer.

Resistance tubes.—The tubes thus far employed have been of either agglomerated carbon or Acheson graphite, in both cases of $\frac{1}{2}$ inch inside diameter and 12 inches long, $1\frac{1}{2}$ inch at each end being clamped in the graphite contact block. The carbon tubes are molded, of $\frac{15}{16}$ inch O. D. These gave good results only after the furnace had been heated two or three times, being allowed to cool and the

tube cleaned after each heat. The first heating gave off considerable water vapor, also smoke from the constituents of the binding material of the carbon tube. The latter formed a slag at the ends of the tube, almost closing them, so that nothing further could be done until the chamber was opened and the slag cleared away. A strong impurity spectrum was also given, especially of sodium and aluminum. After the second heat there was much less trouble from these sources, and a number of very satisfactory runs were made with these tubes. A further troublesome feature of the carbon tubes is the fact that after a run at a high temperature, the carbon was thoroughly graphi tized, making a considerable change in the resistance of the tubes.

Acheson graphite has given better satisfaction in many respects as a material for tubes. There is no appreciable water vapor given off, no slag formed, the material remains apparently unchanged, and the disturbance from impurities in the graphite is very small. The tubes were bored out and turned to $\frac{23}{32}$ inch O. D.

With both the carbon and graphite tubes, the ends of the tubes and also the holes in the graphite blocks for the tube and for the copper electrodes were thoroughly rubbed with powdered Acheson graphite, grade 1310, which filled the pores of the surfaces and greatly improved the contacts.

Pressure chamber.—The steel chamber to contain the cartridge described in the foregoing is shown in each of the photographs, Figs. 1 and 2, Plate XXIII. The length of the chamber without the heads is 24 inches, the internal diameter 8 inches, the walls having a ruling thickness of $1\frac{1}{2}$ inch, thickened at the ends with flanges 3 inches thick and 2 inches wide. In each of these flanges there are twelve steel bolts of $1\frac{1}{4}$ inch diameter to hold the heads. The head to which the cartridge is attached contains, besides the insulated bushings for the passage of the electrode tubes, a bronze window holder which screws into the center of the head and is provided with a high-pressure glass window in the form of a truncated cone with large end inside, the metal around the window being cooled with a special water jacket. For the work thus far, which has been done with the chamber pumped out, a piece of plate glass has been cemented on the outside of the window holder. The second head has a similar window holder and contains in addition two holes into which fit inlet

and outlet pipes for gases and the connections for the high-pressure apparatus. The chamber has been tested to stand a working pressure of 200 atmospheres.

The steel chamber requires efficient water cooling, which is provided for by riveting a cylinder of galvanized sheet iron to the end flanges, allowing the space between them to be filled with water. The water enters below at one end of the jacket and leaves above at the other end.

Current supply.—The current is taken from a 50 K. W. transformer, fed with 2000 volts and giving 5, 10, 20, and 30 volts in the secondary. No regulating resistance is used, the different voltages being used for different temperatures of the furnace, and the voltage is put directly on the furnace tube with as little loss in the connections as possible.

Operation of furnace.—The furnace chamber, whose total weight is over 600 lbs., lies in a rack of cast iron, which rests in turn on the planed ring of an iron plate imbedded in the top of a masonry pier. The rack is centered by a pivot in the bed-plate, and may thus be turned in a horizontal plane to any desired angle. To remove the cartridge from the pressure chamber, the head to which the cartridge is attached is clamped firmly in the carriage shown to the right in the photograph, Plate XXIII, Fig. 2. This is a wooden ring mounted on a base provided with casters. The carriage is then rolled back on a table prepared for it, drawing the head horizontally off the bolts and with it the cartridge. The latter when drawn clear of the chamber is supported by a wooden stand on the table. The graphite blocks, resistance tube, and jacketing material are then placed in position in the open, where all of the parts can easily be put in correct adjustment. The substance to be vaporized is placed in the resistance tube and the cartridge returned to the chamber. The furnace is then turned back into position so that the two windows and the furnace tube in line with them are pointing toward the mirror above the slit of the large Littrow spectrograph,[1] in which position the heavy copper bars from the transformer connections fit into place on the ends of the copper pipe electrodes.

When the furnace is in position, if a run in vacuum is desired, the

[1] See *Contributions from the Mount Wilson Solar Observatory*, No. 27.

air is removed by means of a Geryk pump, the water is turned on through the several jackets, and the closing of a primary switch causes the current to pass.

Optical arrangement.—As has been noted, the furnace allows the spectrum of the substance vaporized in the resistance tube to be observed to equal advantage from either end. The Littrow grating spectrograph is usually used with the lens at the 13-foot focus. The light passes through a lens to a mirror which reflects it vertically to the slit. An image of the interior of the tube is thus formed on the slit, the middle portion of the length of the tube being in the sharpest focus. The image is made about the same size as the object and the slit is chosen of such length that only the light from the center of the image passes through, the image of the white-hot walls and of any solid matter in the tube being entirely cut out.

The comparison arc for the identification of lines is placed directly back of the furnace so that its light passes through the furnace tube and gives an image slightly out of focus on the slit if the same condensing lens is used. The proper position of the lens for the furnace tube being known, the adjustment of the image of the tube on the slit may be made by means of the light from the arc, so that all is in readiness for an exposure when the furnace is turned on.

The window at the other end of the furnace may be used to photograph with a prism spectrograph on a movable table, enabling a series of short exposures to be made simultaneously with the longer exposures required by the Littrow; or it may be used to watch the condition of the spectrum by means of a direct-vision spectroscope, enabling the exposures to be begun and ended at the proper time. A third use is for temperature measurements with the Wanner pyrometer during the progress of an exposure with the Littrow spectrograph.

Temperature measurements.—A Wanner pyrometer was used to measure the temperature of the hottest part of the furnace tube. This instrument has a Reichsanstalt calibration, and judging by the good agreement of its readings with and without the dark glass, is highly reliable. The measurements so far taken have been for the purpose of showing the temperatures corresponding to a certain voltage used on the furnace when a given tube was employed. Tem-

perature measurements have not been made when a spectrum was being photographed, as the small window in the furnace head does not allow satisfactory temperature measurements to be made without a bright background such as a graphite plug placed in the central part of the tube. For this reason, special runs of the furnace were made for the pyrometer measurements, reproducing as nearly as possible the conditions under which a certain spectrum was observed. These observations have given results sufficiently concordant among themselves to give a reliable value for the approximate temperature corresponding to each voltage on the furnace. Thus with graphite tubes the following measurements were obtained:

Volts	Degrees C.	Number of Observations
5	1700–1800	4
10	2400–2500	4
20	2850–2950	2
30	3015	1

For the carbon tubes a lower series of temperatures was obtained, 1650°, 2570°, and 2770° being found from one set of readings for 10, 20, and 30 volts respectively.

These temperatures were measured for a certain length and size of tube and would of course vary if any of the dimensions were changed. They are given here merely to show the range of temperatures available in the work already done. Each set of observations was made for a different run of the furnace with a different tube, mounted in as nearly the same way as possible. The temperature was taken in each case after the current had passed long enough to bring the tube to a fairly steady condition, attained only after the jacketing material had become highly heated; and at the lower voltages some increase over the above temperatures could be obtained by prolonging the run.

It will be noted that the use of 30 volts does not give a proportional increase in temperature over 20 volts and that the highest temperature obtained with the graphite tube (which would probably have been increased only slightly, if at all, by the use of a still higher voltage) is considerably below the temperature of the positive pole of the carbon arc, measured by Waidner and Burgess[1] with the

[1] *Bulletin, Bureau of Standards,* Vol. I, pp. 109–124.

Wanner pyrometer as about 3400° C. With the carbon tubes, the graphitizing of the material, which occurred after a short run at 20 volts and thereby lowered the resistance of the tube, was doubtless in some measure responsible for this; but in the case of the graphite tubes the material appears to remain unchanged. In the light of the data thus far obtained, it seems fair to ascribe this condition to the lively vaporization of the carbon (or graphite) which begins at about 2500° C. and becomes so vigorous at 2800° C. that the life of the thin graphite tube is very short when used at 20 and 30 volts. The carbon spectrum was regularly obtained with the graphite tubes at the 10-volt temperature and became very intense at the higher voltages. We have thus conclusive evidence that the vaporizing point of carbon is much below the temperature of the hottest part of the carbon arc, making it probable that the high temperature of the positive terminal is due to a superheating caused by a bombardment of this pole by particles impelled by the electric forces present in the arc.

It has been noted that a graphite plug in the middle of the tube was used when making a pyrometer measurement, in order to provide an incandescent surface at which to direct the instrument. It should give measurements of the same accuracy if the pyrometer were directed at the inner surface of the incandescent tube, and a measurement was made to test this with the bronze window holder removed, giving an opening $1\frac{3}{4}$ inch in diameter in the steel head, which was covered by a piece of plate glass. With this aperture, the pyrometer was directed alternately at the plug and at the adjacent wall of the tube, and the readings were practically the same, showing that the measurements made with the plug in the tube were approximately correct for the wall in the middle portion. When the tube is unobstructed and filled with vapor from any substance placed in it there is of course more or less of a temperature gradient between the wall and the vapor in the center.

SPECTROSCOPIC RESULTS

A series of photographs has been made of the spectra of iron, chromium, titanium, and vanadium with the Littrow spectrograph at its 13-foot focus, using the first order of a plane grating 5 inches

TITANIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4256.18	5	3	4512.88	36	15
4260.91	8	6	4518.18	38	15
4263.28	17	9	4522.97	40	15
4270.30	28	6	4527.48	36	18
4274.73	34	18	4533.42	40	21
4276.55	7	6	4534.97	40	18
4281.49	7	9	4536.25	44	33
4282.85	14	12	4544.83	38	15
4285.15	8	6	4548.93	38	15
4286.15	34	12	4552.62	42	15
4287.55	28	12	4555.64	38	15
4290.07	31	12	4558.28	3	6
4291.32	28	15	4563.60	34	12
4294.28	22	9	4590.11	6	6
4295.91	28	12	4617.41	40	15
4298.82	36	18	4623.24	34	15
4302.08	38	21	4629.47	17	15
4306.07	38	21	4639.83	34	24
4308.64	34	9	4645.36	10	12
4314.95	36	18	4650.16	8	9
4318.83	13	9	4656.60	36	18
4321.82	8	6	4667.76	38	18
4325.30	8	9	4675.27	6	15
4379.40	6	18	4682.08	39	21
4384.85	36	12	4691.50	19	15
4394.04	9	3	4698.94	18	15
4395.17	36	15	4710.34	12	18
4399.92	9	3	4715.46	3	18
4404.42	26	15	4723.32	6	12
4414.29	10	12	4731.33	4	9
4417.88	15	9	4742.94	13	6
4421.92	7	12	4758.30	24	9
4423.00	8	15	4759.44	26	12
4426.24	9	15	4778.44	5	3
4427.28	38	18	4781.91	4	12
4430.19	7	9	4792.65	5	3
4434.15	14	15	4799.95	6	6
4436.75	5	6	4805.25	8	9
4440.49	9	6	4820.56	10	15
4443.97	38	12	4841.00	22	15
4449.32	36	15	4848.62	3	6
4451.07	30	12	4856.18	12	9
4453.48	38	18	4868.44	8	9
4455.48	36	15	4870.28	10	12
4457.59	40	21	4885.25	15	15
4463.70	9	12	4900.08	14	12
4465.96	20	12	4913.76	10	15
4471.40	22	15	4419.99	2	6
4475.00	8	12	4921.90	4	9
4480.72	8	3	4928.50	3	9
4481.41	35	12	4973.25	2	6
4482.84	8	9	4975.52	3	9
4489.24	19	9	4978.39	3	9
4496.33	22	18	4981.91	40	21

TITANIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4989.33	3	9	5210.55	40	30
4991.24	40	21	5219.88	4	21
4997.26	3	15	5224.71	8	18
4999.67	40	21	5238.77	3	18
5001.16	5	12	5246.75	1	9
5007.42	38	18	5251.14	4	18
5009.81	2	15	5266.20	6	18
5013.45	5	9	5283.63	6	9
5014.40	40	21	5295.95	5	15
5016.32	14	18	5297.42	5	9
5020.17	20	18	5298.61	3	12
5023.02	18	18	5369.81	7	18
5025.00	15	15	5397.28	8	24
5036.10 } 5036.65 }	20	12	5404.25	5	18
			5409.81	8	24
5038.55	16	12	5426.48	2	24
5040.12	24	15	5429.37	4	21
5043.77	2	15	5436.93	2	12
5045.58	2	18	5438.53	2	9
5053.06	2	12	5446.80	7	27
5064.82	30	21	5449.40	4	6
5087.24	3	15	5453.88	7	24
5113.64	4	15	5460.72	7	24
5120.60	7	12	5471.43	6	12
5145.62	8	15	5474.43	9	18
5147.63	7	21	5477.92	12	15
5152.36	6	21	5481.64	10	21
5173.94	34	27	5488.44	8	12
5193.15	39	27	5490.38	16	21
5194.25	2	6	5504.10	14	9
5206.30	8	21	5512.72	38	27
5208.08	8	18	5514.58	40	42

VANADIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4090.70	38	15	4128.25	44	18
4092.83	42	15	4132.13	43	18
4095.64	32	15	4134.61	42	18
4099.93	33	12	4143.02	9	12
4102.32	26	15	4160.57	11	15
4105.32	42	15	4180.99	26	21
4109.94	42	15	4183.59	11	12
4111.92	44	18	4191.70	14	15
4113.65	9	6	4194.17	12	15
4115.32	42	15	4209.98	15	21
4116.64	40	24	4216.52	21	15
4119.58	15	6	4232.62	16	9
4121.13	9	6	4234.12	14	15
4123.65	44	15	4235.90	8	6

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4251.45	6	9	4469.88	40	15
4257.53	5	6	4474.89	26	15
4259.46	6	15	4480.20	8	18
4265.28	5	6	4489.06	42	24
4268.78	40	15	4491.35	10	3
4271.71	40	15	4496.26	11	27
4277.12	35	9	4502.12	15	15
4283.06	4	9	4506.41	6	6
4284.19	34	12	4514.36	9	3
4286.57	5	15	4517.77	5	27
4287.97	4	15	4524.38	21	6
4291.97	23	18	4529.47	16	6
4293.25	3	9	4530.97	6	6
4296.28	19	18	4537.84	6	3
4306.35	22	27	4540.18	6	9
4307.33	20	15	4545.57	42	12
4309.95	22	27	4552.05	4	24
4330.18	42	24	4554.21	6	24
4332.98	41	21	4560.90	38	12
4341.15	43	24	4570.60	7	6
4353.02	44	27	4571.96	35	12
4356.10	13	21	4577.36	42	33
4363.48	6	15	4579.38	5	9
4368.25	19	18	4580.57	42	30
4379.38	48	39	4586.54	43	45
4384.07	42	6	4591.39	17	6
4384.87	45	33	4594.27	44	48
4390.13	47	30	4600.34	3	3
4392.24	8	18	4606.33	18	27
4395.40	44	30	4607.40	2	6
4400.74	43	24	4611.10	5	9
4405.20	30	15	4619.97	38	27
4406.80	45	24	4624.62	10	18
4407.85	44	21	4626.67	9	15
4408.36	44	33	4635.35	16	36
4412.30	18	24	4640.25	8	21
4416.63	42	27	4640.92	6	12
4420.08	19	21	4646.59	17	21
4421.73	41	27	4666.33	4	24
4423.41	10	15	4670.66	26	21
4426.17	42	39	4684.64	3	6
4428.68	40	24	4687.10	5	15
4429.95	32	33	4710.74	9	24
4434.80	11	6	4717.85	7	9
4436.31	42	27	4721.70	6	9
4438.02	40	30	4723.06	7	9
4441.88	44	30	4742.79	4	6
4444.40	42	27	4766.80	8	6
4449.77	8	15	4776.54	14	9
4452.19	40	21	4784.65	3	15
4457.65	43	42	4786.70	12	6
4459.93 } 4460.46 }	48	36	4793.10	2	3
			4797.07	15	6
4462.56	41	18	4799.94	4	15

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4807.70	18	6	5128.71	5	18
4827.62	28	30	5138.58	4	9
4832.59	26	24	5139.74	3	9
4833.17	26	21	5148.95	3	21
4851.65	40	27	5159.56	3	15
4864.93	39	21	5193.18	6	21
4875.66	41	21	5195.01	7	6
4881.75	42	24	5234.31	7	6
4891.81	3	9	5402.17	12	6
4900.84	4	9	5415.51	17	6
4904.59	7	6	5418.33	3	9
4925.83	5	6	5434.43	6	18
4932.24	2	6	5437.93	2	9
5014.83	3	18	5443.50	1	30
5064.83	2	9	5488.18	17	12
5105.37	6	6	5490.22	5	18

in length with 14,438 lines to the inch. The iron spectrum has been photographed for the region from λ 3700 to λ 6700. The plates thus far taken for the other substances extend only from λ 4000 to λ 5500. Each spectrum was obtained for at least two different temperatures, an exposure being made first with a low voltage on the furnace and then another with a higher voltage, the current being broken for only a few seconds, so that the higher voltage started with the tube and jacketing highly heated from the previous run, and the second exposure was made after a much higher temperature had been established. The exposure times varied with the substance, temperature, and region of spectrum, from one minute at the highest temperatures to 30 minutes for a spectrum barely visible in the direct-vision spectroscope. Ten minutes were usually ample for any spectrum at 2500° C. or higher. The change of temperature during these exposures was not large, and could be kept nearly constant when desired by watching selected parts of the spectrum, especially the carbon flutings, in the visual spectroscope and breaking the current for a few seconds when these became too bright.

It is not the purpose of the present paper to discuss the effects of different temperatures upon spectra; so that in the foregoing tables only a comparison of the arc and furnace spectra of titanium and vanadium is given, with the object of showing the richness of the furnace spectra as compared with the arc and to give a general view

of the relative intensities of lines in the two sources, as these spectra have not heretofore been obtained, to the writer's knowledge, by non-electrical methods. These furnace spectra were among the first photographed and were obtained with carbon tubes at about 2700°–2800° C. The arc spectrum was obtained on the same kind of plate (Cramer Isochromatic) with all optical arrangements the same.

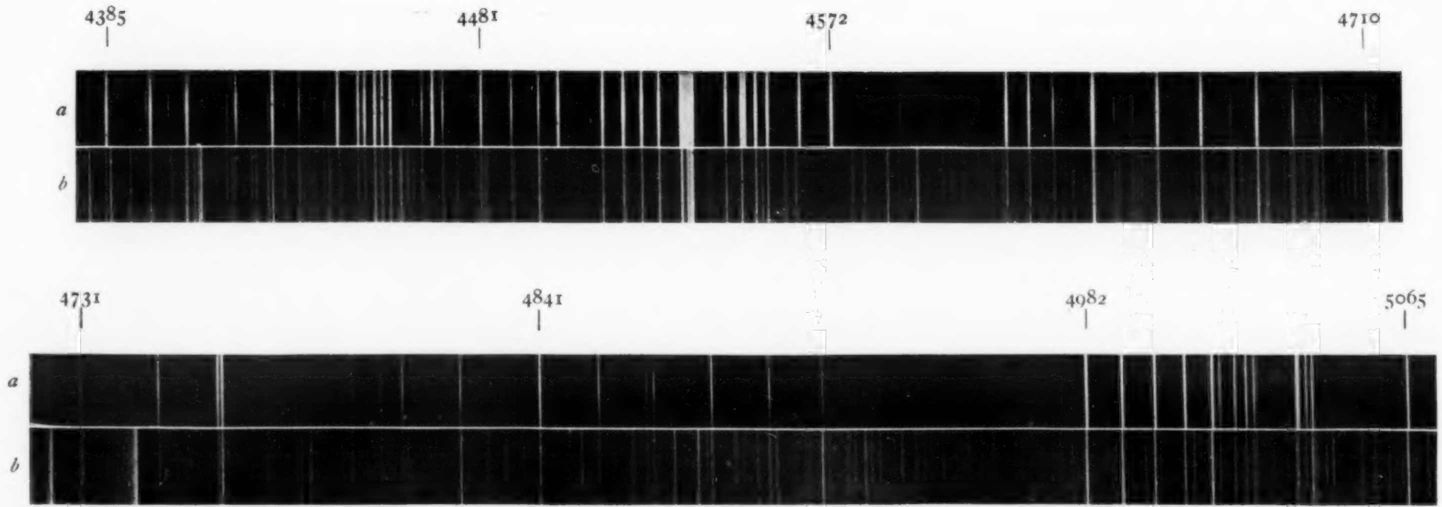
The intensities of lines for both arc and furnace spectra were measured by means of a photographic scale made with the Littrow spectrograph by illuminating the slit with a constant voltage incandescent lamp and photographing the direct reflection from the grating with exposures ranging from 1 to 40. This gave a fairly satisfactory scale as regards gradation in blackness. The change in width of the lines of the scale with exposure time was also measured and a curve plotted to show this variation. This scale was placed in a special holder on a Zeiss spectrocomparator, so that when a spectrum plate was mounted on the moving carriage any line of the spectrum could be brought into the field of the eyepiece opposite the lines of the scale, giving, except for overexposed and reversed lines, a good measure of the intensity by selecting the line of the scale having the same blackness as the spectrum line. If the spectrum line was widened, this was considered in the final estimate of its intensity. Lines of intensity greater than 40 were estimated as closely as possible by extrapolation.

After the tables for arc and furnace were prepared, all of the intensities of furnace lines were multiplied by 3, which gave the spectrum as a whole about the same strength as that of the arc and rendered the relative differences more distinct. Although this proceeding is open to objection from the photometric point of view, it serves well for the rough comparison aimed at in these tables, where the differences in intensity are usually large.

Photographs of the arc and furnace spectra are reproduced in Plates XXIV and XXV for a part of the region covered by the tables of titanium and vanadium lines. Each furnace spectrum shows the spectrum of the other element as an impurity. These photographs, considered in connection with the tables, offer material which may be discussed under the following heads:

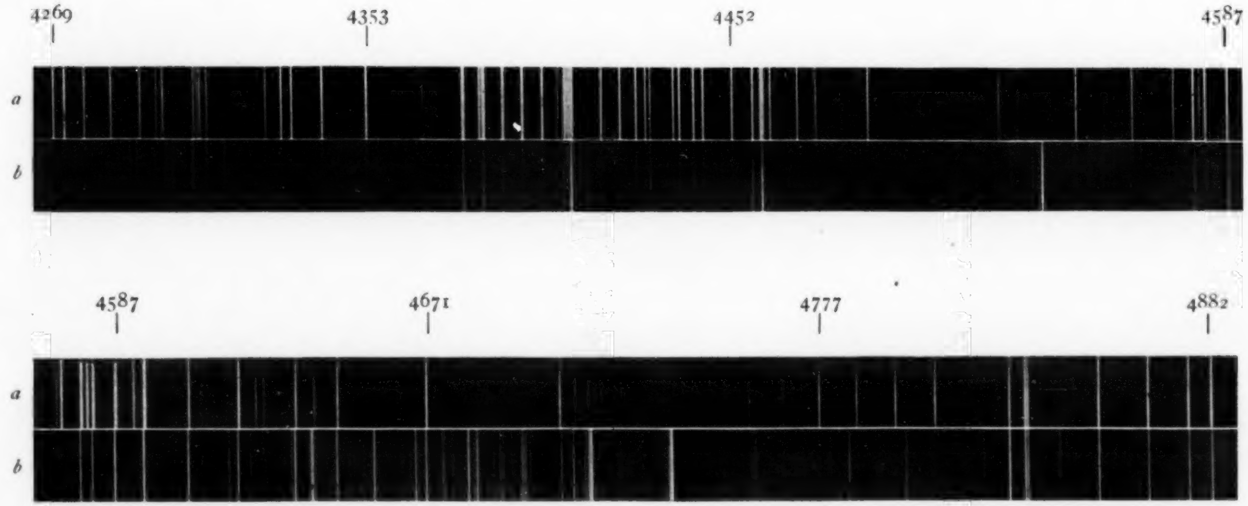
1. The question of temperature radiation. There is nothing to

PLATE XXIV



SPECTRUM OF TITANIUM
(*a*) In Carbon Arc; (*b*) In Electric Furnace

PLATE XXV



SPECTRUM OF VANADIUM
(*a*) In Carbon Arc; (*b*) In Electric Furnace

indicate that temperature was not the sole and sufficient agent in producing these spectra. Electrical action, other than the ionization at a heated surface, was entirely excluded, no arc of any sort being present. As to chemical action, the small residue of air in the pumped-out chamber should have had its oxygen consumed long before the metal in the tube reached its vaporizing point, and if this were not the case, it is scarcely conceivable that enough could have reached the substance at the middle of the white-hot tube to give the vigorous radiation observed as long as a trace of the metal remained. To be sure, some impurities are contained in the material of the carbon tubes; but the tubes of Acheson graphite, containing extremely little foreign matter, were fully as efficient in giving the spectra of the substances placed in them. The spectroscopic evidence on this point is the fact that titanium gives a pure line spectrum, with no trace of the flutings given in the flame of the arc burning in air and generally ascribed to the oxide.

2. The number of lines given by the furnace as compared to the arc. For titanium the rather strong arc photograph gives 31 lines of intensity 3 or higher (1 indicating a line barely visible on the plate) which do not appear on the furnace plate for this region (λ 4250 to λ 5500), the furnace plate thus showing 85 per cent. of the arc lines. For vanadium, the number is relatively smaller, 73 per cent. of the arc lines being given by the furnace from λ 4100 to λ 5500. Longer exposure with the furnace would doubtless have brought out more of the weak lines, as none of the furnace lines attained maximum intensity.

3. The temperatures at which the carbon flutings appear and reach high intensity have been given. The band at λ 4737 may be seen in the reproductions of both the titanium and vanadium furnace spectra. This and the band at λ 5165 are easily obtained of considerable intensity. The cyanogen bands at λ 3883 and λ 4216 also appear, but faintly on account of the small supply of nitrogen.

4. Mention may be made here of the behavior of the "enhanced lines," those given relatively strong in the electric spark as compared to the arc. Eleven of the enhanced lines of titanium given by H. M. Reese[1] appear in the table of titanium furnace lines, and with one exception

[1] *Astrophysical Journal*, **19**, 322, 1904.

are relatively much weaker in the furnace that in the arc. Five enhanced lines are among the 31 arc lines not found on the furnace plate, the two strongest in this list, λ 4501.43 and λ 4572.15, being given by Reese as enhanced in the ratio 9 to 5. A full consideration of this interesting point, together with a study of the enhanced lines of iron, will be given when tables showing the effects of different furnace temperatures upon the several spectra are published.

5. An examination of the tables for both vanadium and titanium shows that generally the lines of shorter wave-length are much stronger in the arc than in the furnace; while in the green region the furnace lines are as a rule relatively stronger. As these lists of intensities for arc and furnace were made up quite independently, the showing made when they are placed side by side is striking evidence of a shift of maximum in the spectrum due to a temperature difference in the two sources.

MOUNT WILSON SOLAR OBSERVATORY
August 20, 1908

ON THE PROBABLE EXISTENCE OF A MAGNETIC FIELD IN SUN-SPOTS[1]

By GEORGE E. HALE

The discovery of vortices surrounding sun-spots, which resulted from the use of the hydrogen line $H\alpha$, for solar photography with spectroheliograph,[2] disclosed possibilities of research not previously foreseen. Photographs taken daily on Mount Wilson with this line suggest that all sun-spots are vortices, and provide material for a discussion of spot theories which will soon be undertaken. Revealing, as they do, the existence of definite currents and whirls in the solar atmosphere, they afford the requisite means of testing the operation in the sun of certain physical laws previously applied only to terrestrial phenomena. The present paper describes an attempt to enter one of the new fields of research opened by this recent work with the spectroheliograph.

ELECTRIC CONVECTION

In 1876 Rowland discovered that an electrically charged ebonite disk, when set into rapid rotation, produced a magnetic field, capable of deflecting a magnetic needle suspended just above the disk.[3] It thus appeared, in accordance with Maxwell's anticipation, that a rapidly moving charged body gives rise to just such effects as are caused by an electric current flowing through a wire. Rowland's whirling disk therefore corresponds to a wire helix, within which a magnetic field is produced when a current is passed through it.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 30. A preliminary note bearing the title "Solar Vortices and the Zeeman Effect," was sent to *Nature* for publication June 30. A brief abstract of this note appeared in *Nature* for August 20, together with a very interesting paper by Professor Zeeman, who was kind enough to examine some copies of my photographs, taken with the rhomb and Nicol in June. My own note was subsequently printed in *Publications of the Astronomical Society of the Pacific*, **20**, 220, 1908.

[2] Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Rowland, "On the Magnetic Effect of Electric Convection," *American Journal of Science* (3), **15**, 30, 1878.

Recent studies of the discharge of electricity in gases prove that gases and vapors, when ionized by one of several means, contain electrically charged particles. Moreover, at high temperatures carbon and many other elements which occur in the sun emit negatively charged corpuscles in great numbers; the complementary positively charged particles must also be present, more or less completely separated from the negative corpuscles.[1] Thus electromagnetic disturbances on a vast scale may result from the rapid motions of charged particles produced by eruptions or other solar disturbances.

Soon after the discovery of the vortices associated with sun-spots, it occurred to me that if a preponderance of positive or negative ions or corpuscles could be supposed to exist in the rapidly revolving gases, a magnetic field, analogous to that observed by Rowland in the laboratory, should be the result. An equal number of positive and negative ions, when whirled in a vortex, would produce no resultant field,[2] since the effect of the positive charges would exactly offset that of the negative charges. But Thomson's statement regarding the possible copious emission of corpuscles by the photosphere, and the tendency of negative ions to separate themselves, by their greater velocity, from positive ions, led to the belief that the conditions necessary for the production of a magnetic field might be realized in the solar vortices.

Thanks to Zeeman's discovery of the effect of magnetism on radiation it appeared that the detection of such a magnetic field should offer no great difficulty, provided it were sufficiently intense. When a luminous vapor is placed between the poles of a powerful magnet the lines of its spectrum, if observed along the lines of force, appear in most cases as doublets, having components circularly polarized in opposite directions. The distance between the components of a given doublet is directly proportional to the strength of the field. As different lines in the spectrum of the same element are affected in different degree, it follows that in a field of moderate strength many of the lines may be simply widened, while others, which are exceptionally sensitive, may be separated into doublets.

[1] J. J. Thomson, *Conduction of Electricity through Gases*, p. 165.

[2] Unless separated by centrifugal force, as suggested by Professor Nichols.

THE SUN-SPOT SPECTRUM

It has long been known that the spectrum of a sun-spot differs from the ordinary solar spectrum in several particulars. If, for example, we examine the iron lines in a spot, we find that some of them are more intense than in the solar spectrum, while others are weaker. Again, we perceive that many of the spot lines are widened, and that the degree of widening varies for different lines. Finally, if the observations are made with an instrument of high dispersion, it will be seen that some of the iron lines, which are single in the solar spectrum, are double in the spot spectrum. Such double lines were first seen by Young in 1892 with a large spectroscope attached to the 23-inch Princeton refractor. Walter M. Mitchell, who subsequently observed them with the same instrument, described the doublets as "reversals," which they closely resemble. Mitchell's papers contain a valuable series of observations of these "reversals" and other sun-spot phenomena.[1]

Our previous investigations in this field on Mount Wilson may be summarized as follows:

1. The application of photography to the study of sun-spot spectra. A Littrow or auto-collimating spectrograph of 18 feet (5.5 m) focal length, used with the Snow telescope, gave good results, and permitted a great number of spot lines and bands, not previously known, to be recorded.[2] On the completion of the tower telescope last autumn, these observations were continued with a vertical spectrograph of 30 feet (9.1 m) focal length.[3] Although the only grating available for work in the higher orders is a 4-inch (10 cm) Rowland, having 14,438 lines to the inch (567 to the mm), employed in my experiments in photographing sun-spot spectra at the Kenwood and Yerkes

[1] Walter M. Mitchell, "Reversals in the Spectra of Sun-Spots," *Astrophysical Journal*, **19**, 357, 1904; "Researches in the Sun-Spot Spectrum, Region F to *a*," *ibid.*, **22**, 4, 1905; "Results of Solar Observations at Princeton, 1905–1906," *ibid.*, **24**, 78, 1906.

[2] Hale and Adams, "Photographic Observations of the Spectra of Sun-Spots," *Contributions from the Mount Wilson Solar Observatory*, No. 5; *Astrophysical Journal*, **23**, 11, 1906.

[3] Hale, "The Tower Telescope of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Observatories,[1] the results secured with this instrument are very satisfactory, greatly surpassing those obtained with the 18-foot spectrograph. They give the first photographic records of the "reversals" or doublets seen visually by Young and Mitchell, and reveal thousands of faint lines beyond the reach of visual observation.

2. The preparation of a photographic map of the sun-spot spectrum and a catalogue of all the lines. A preliminary map, consisting of 26 sections of 100 Ångströms each, covering the region λ 4600–7200, was prepared last year by Mr. Ellerman from negatives made with the 18-foot spectrograph, and supplied to visual observers taking part in the sun-spot work of the International Solar Union. A much better map, to be made from negatives obtained with the tower telescope and 30-foot spectrograph, will be ready, it is hoped, within a year. The catalogue of lines, which involves a great amount of measurement for the determination of wave-lengths, is well advanced, and one section has been published by Mr. Adams.[2]

3. The identification of the numerous lines which constitute the flutings in the spot spectrum. Photographs of the spectra of titanium oxide, magnesium hydride, and calcium hydride,[3] made in our laboratory by Dr. Olmsted, have furnished the material for this purpose. The measurement of the lines in these flutings is well advanced.

4. The interpretation of the change of the relative intensity of lines observed in passing from the solar spectrum to the spot spectrum. Investigations on the spectra of iron, manganese, chromium, titanium, vanadium, and other metals conspicuous in spots, made with the arc, spark, and flame, indicated that this change is due to a reduction of the temperature of the spot vapors.[4] Subsequent work with a new

[1] Hale, "Solar Research at the Yerkes Observatory," *Astrophysical Journal*, **16**, 211, 1902.

[2] Adams, "Preliminary Catalogue of Lines Affected in Sun-Spots, Region λ 4000 to λ 4500," *Contributions from the Mount Wilson Solar Observatory*, No. 22; *Astrophysical Journal*, **27**, 45, 1908.

[3] Olmsted, "Sun-Spot Bands Which Appear in the Spectrum of a Calcium Arc Burning in the Presence of Hydrogen," *Contributions from the Mount Wilson Solar Observatory*, No. 21; *Astrophysical Journal*, **27**, 66, 1908.

[4] Hale, Adams, and Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906; Hale and Adams, "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 15; *Astrophysical Journal*, **25**, 75, 1907.

electric furnace by Dr. King,[1] the details of which have not yet been published, seems to leave little doubt that this explanation is correct. It is supported by the presence in the spot of compounds which appear to be dissociated at the higher temperature outside the spot, and by the resemblance of spot spectra to the spectra of red stars.[2]

While our investigations have thus furnished a plausible explanation of some of the characteristic phenomena of sun-spot spectra, the widening of lines and the presence of doublets are among the remaining peculiarities that demanded consideration. As we have seen, however, these very peculiarities are precisely what would be expected if a magnetic field were present. Prompted by the theoretical considerations outlined above, and encouraged by their apparent agreement with the facts of observation, I decided to test the components of the spot doublets for evidences of circular polarization and to seek for other indications of the Zeeman effect.

METHOD OF OBSERVATION

The tower telescope forms an image of the sun, about 6.7 inches (17 cm) in diameter, on the slit of a vertical spectrograph, of 30 feet focal length. This instrument, to which reference has already been made, stands in a well with concrete walls, the grating being about 26½ feet (8 m) below the surface of the ground. The temperature at the bottom of the well is so constant that exposures of any desired length may be given, without danger of a shift of the lines resulting from expansion or contraction of the grating. A Fresnel rhomb and Nicol prism[3] are mounted above the slit, so that the light of the solar image passes through them. If the doublets in spots are produced by a magnetic field, the light of their components, circularly polarized in opposite directions, should be transformed by the rhomb into two

[1] King, "An Electric Furnace for Spectroscopic Investigations, with Results for the Spectra of Titanium and Vanadium," *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] Hale and Adams, "Sun-Spot Lines in the Spectra of Red Stars," *Contributions from the Mount Wilson Solar Observatory*, No. 8; *Astrophysical Journal*, **23**, 400, 1906; Adams, "Sun-Spot Lines in the Spectrum of *Arcturus*," *Contributions from the Mount Wilson Solar Observatory*, No. 12; *Astrophysical Journal*, **24**, 69, 1906.

[3] Obtained for this purpose in 1905, when the idea of searching for the Zeeman effect in sun-spots had already occurred to me. A visual test of the spot lines for plane polarization, made with the 18-foot spectrograph in 1906, before we had photographed the doublets, gave negative results.

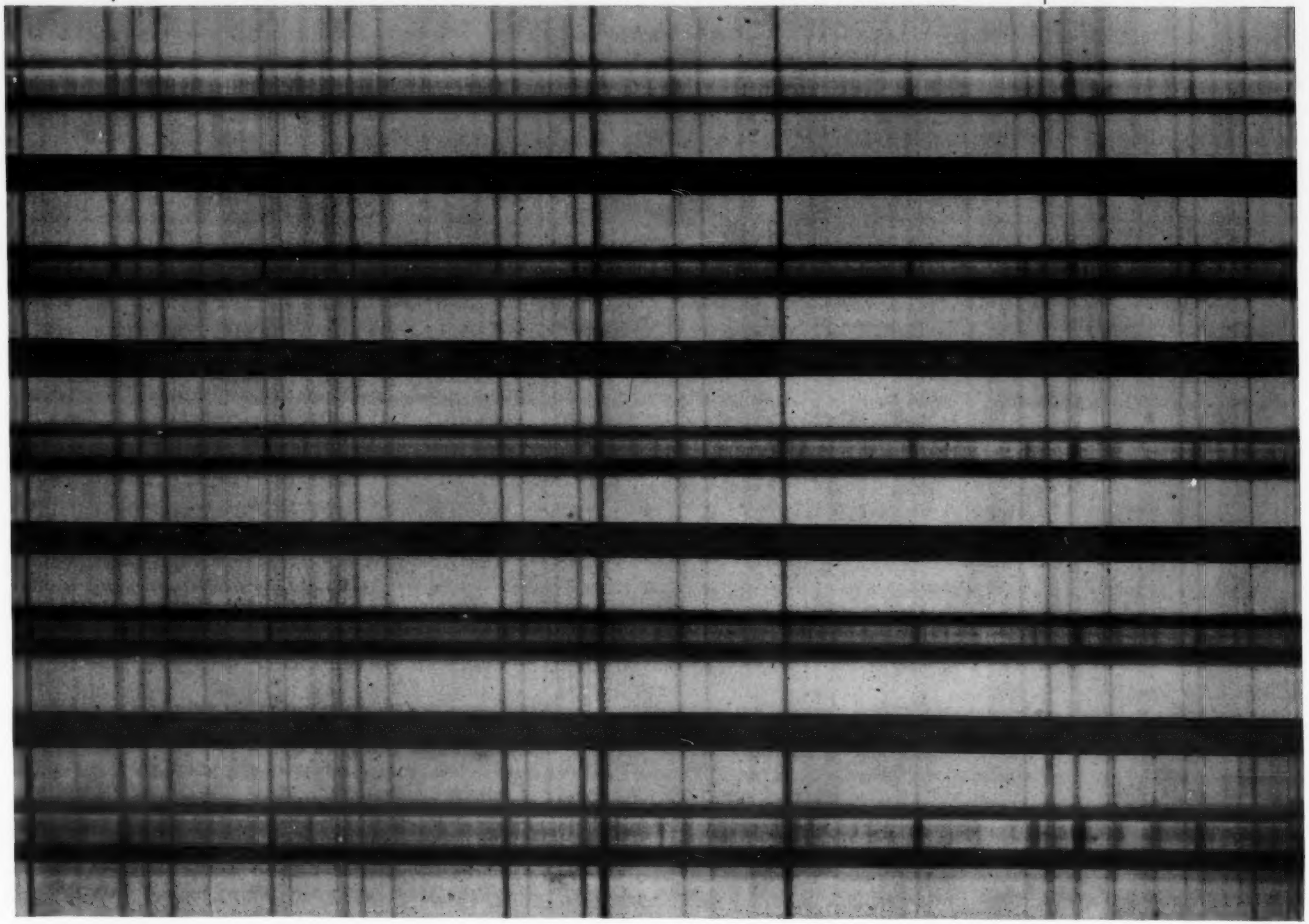
plane polarized rays, differing 90° in phase. Thus, in a certain position of the Nicol, the light from the red component should be transmitted and that of the violet component cut off. When rotated 90° in azimuth, the Nicol should transmit the violet component and cut off the red component. Complete extinction of either component is hardly to be expected, because the light from the spot does not, in general, come exactly along the lines of force, and the doublets may therefore exhibit some traces of elliptical polarization. Moreover, the beam of sunlight undergoes two reflections on the silvered surfaces of the coelostat and second mirrors of the tower telescope, where elliptical polarization must again be introduced.[1] By setting the rhomb at the proper angle, the latter effect, which is not very large, can be almost wholly eliminated, but the former may play some part, even when the spot is at the center of the sun.

The light of the spot, after transmission through the rhomb and Nicol, comes to a focus in the plane of the slit. While photographing the spot spectrum the slit is covered except at its central part, where a portion corresponding in length (from 1 to 2 mm) to the diameter of the umbra, receives the light. During the exposure, which may continue from a few minutes to over an hour, the image of the umbra is kept as nearly as possible central on the slit, any irregularities in the motion of the driving-clock being corrected by the observer. As the exposure for the spot spectrum is from five to twenty times as long as for the solar spectrum, it is evident that care must be taken to prevent light from regions outside the spot from entering the slit.

For a comparison spectrum sunlight is used, generally from a point in the solar image a short distance away from the spot, where none of the characteristic spot phenomena appear. During the exposure, that part of the slit which previously received the light of the umbra is covered, and sunlight admitted on either side. The light of the comparison spectrum passes through the rhomb and Nicol, both of which occupy the same positions as in the case of the spot. Care is taken to see that the grating is fully illuminated, both for the spot and comparison spectra, in all positions of the Nicol.

[1] A study of the elliptical polarization of these mirrors has been made by Dr. St. John.

PLATE XXVI



(1) Southern spot, showing red components of doublets. Nicol 29° W. (2) One umbra of northern spot, showing violet components of doublets. Nicol 29° W. (3) Other umbra of northern spot, showing violet components of doublets. Nicol 29° W. (4) Some umbra of northern spot, showing red components of doublets. Nicol 61° E. (5) Spot spectrum without rhomb or Nicol, showing both components of doublets. Scale: 1 Ångström=6 mm.

CIRCULAR POLARIZATION ALONG THE LINES OF FORCE

My first observations were made on June 24, in the second order of the grating, but the results were not conclusive. On June 25 I obtained some good photographs, in the third order, of the region λ 6000–6200, using Seed's "Process" plates, sensitized for the red by Wallace's three-dye formula.[1] These clearly showed a reversal of the relative intensities of the components of spot doublets when the Nicol was turned through an angle of 90°. Moreover, many of the widened lines were shifted in position by rotation of the Nicol, indicating that light from the edges of these lines is circularly polarized in opposite directions. The displacements of the widened lines appeared to be precisely similar in character to those detected by Zeeman in his first observations of radiation in a magnetic field.

A series of photographs, made with the Nicol set at various angles, soon showed the two positions giving the maximum effect. At these positions the weaker components of the strongest doublets are not always completely cut off, but their intensities are greatly reduced. Sometimes hardly a trace of the weaker component remains, as may be seen in the case of the vanadium doublet at λ 5940.87 (Plate XXVI). In this plate No. 5 shows the doublet in the ordinary spot spectrum, photographed without the rhomb and Nicol. No. 4, from a photograph (T 190) made with the Nicol set at 61° E., shows only the red component of the doublet. No. 3 illustrates the effect of turning the Nicol 90°: only the violet component remains. Other spot lines in these photographs change in a similar way.

Photographs like these seemed to leave no doubt that the components of the spot doublets are circularly polarized in opposite directions. Since the only known means of transforming a single line into such a doublet is a strong magnetic field, it appeared probable that a sun-spot contains such a field, and that the widening and doubling of the lines in the spot spectrum result from this cause. But much remained to be done before the proof could be regarded as complete.

In the first place, it was necessary to make sure that the displacement of the lines other than doublets was not due to instrumental causes, such as a change in the illumination of the grating produced by rotating the Nicol. As already stated, care was always taken to

[1] *Astrophysical Journal*, **26**, 299, 1907.

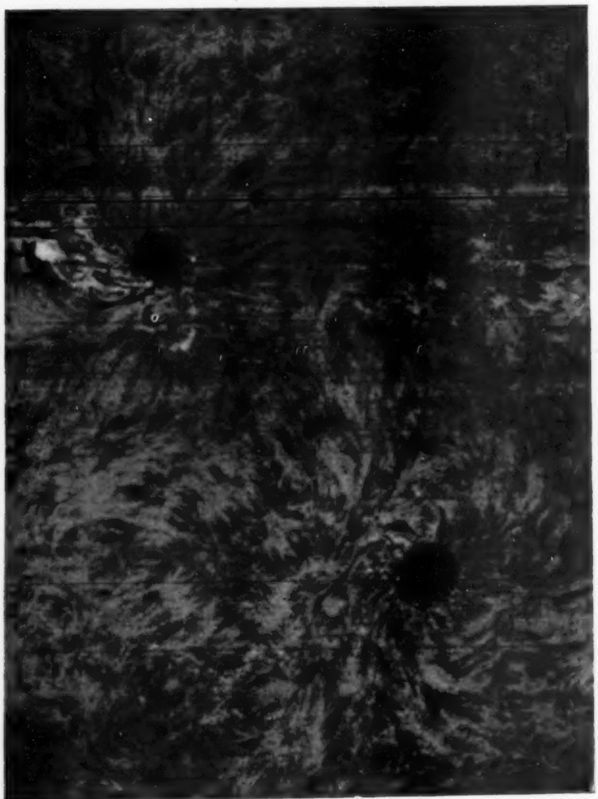
see that the ruled surface was filled with light before making an exposure. Moreover, the magnitude of the displacement was much greater for some lines than for others, and the fact that the shifts were determined with respect to lines of the solar spectrum, whose light had traversed almost the same path as that of the spot in rhomb and Nicol, seemed to leave little room for doubt as to their true character. However, a rigorous test could be applied. The spot spectrum, as well as the solar comparison spectrum, is crossed by lines due to the absorption of water vapor and other gases in the earth's atmosphere. If a change of illumination due to the rotation of the Nicol were concerned, these lines should be displaced from their normal positions. But no such shifts were observed. Furthermore, it is known that the lines of most flutings are not affected by a magnetic field. Accordingly, the cyanogen fluting at λ 3883 was photographed in the spot spectrum, with the Nicol set in two positions 90° apart. Three lines in this fluting, which I have measured on negative T 132, made in the fourth order, show a mean displacement of 0.0004 Ångströms, with respect to the corresponding lines of the solar comparison spectrum. This quantity is well within the error of measurement.[1] We may therefore conclude that the Nicol displaces only those lines which show polarization phenomena.

While measuring this plate, and others taken in the more refrangible part of the spot spectrum, it was found that few of the lines in this region show large shifts. A group of doublets was encountered near λ 4400, the components of which are circularly polarized in opposite directions. In general, however, the shifts produced by rotating the Nicol decrease from the red toward the violet end of the spectrum.

Since this preliminary work I have made over two hundred photographs of spot spectra with polarizing apparatus before the slit. In addition to this collection of plates, numerous photographs of spot spectra, some taken with polarizing apparatus by Dr. St. John, and others made without Nicol or rhomb by Mr. Adams and myself, are available for study. These have been used for the investigation described in the following pages.

[1] The head and several lines of the titanium oxide fluting at λ 5598, which have since been measured by Mr. Adams, also show no displacement when the Nicol is rotated.

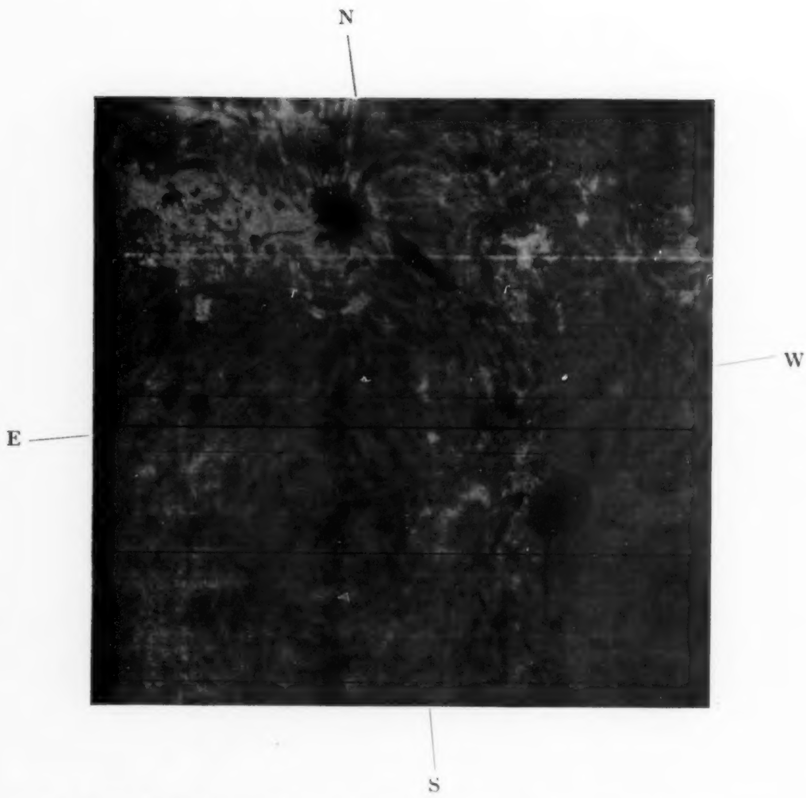
PLATE XXVII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908, September 9, 6^h 20^m A. M. Scale: Sun's Diameter=0.3 Meter

PLATE XXVIII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908, September 7, $6^h\ 20^m$ A. M. Scale: Sun's Diameter=0.3 Meter

REVERSED POLARITIES OF RIGHT- AND LEFT-HANDED VORTICES

A second test, which also bears upon the hypothesis that the field is produced by the revolution of electrically charged particles in the spot-vortex, may now be described. If a Nicol is set so as to cut off the violet component of a doublet observed along the lines of force of a magnetic field, reversal of the current will cause the red component to disappear and the violet component to become visible. Reversal of the direction of the current in a magnet corresponds to reversal of the direction of revolution in a solar vortex. If it could be shown, by an independent method, that in two sun-spot vortices the charged particles are revolving in opposite directions, the red components of the doublets should appear in the spectrum of one spot, and the violet components in that of the other, the position of the rhomb and Nicol remaining unchanged.

Fortunately the spectroheliograph plates indicate the direction of revolution in the solar vortices. The vortices are constantly changing in appearance, and the stream lines are not always clearly defined. Plates XXVII and XXVIII are reproduced from photographs of the sun made by Mr. Ellerman with the 5-foot spectroheliograph on September 9 and 10. They show two spots, one in the northern, the other in the southern hemisphere, with vortices indicating revolution in opposite directions, if we may judge from the curvature of the stream lines.[1] Portions of the spectra of these spots, photographed by myself on September 9, are reproduced in Plate XXVI. No. 1 shows the spectrum of the southern spot, in which the direction of revolution was clockwise, taken with the Nicol set at 29° W. Only the red components of the doublets appear. The northern spot, in which the revolution was counter-clockwise, was then photographed (2). Although the Nicol and rhomb remained in the same position as before, the red components of the doublets are now cut off, while the violet ones are visible. During this exposure the slit was kept on the western umbra of the northern spot, which was divided into two parts by a bridge (not shown in the reproductions). Another exposure, with Nicol and rhomb as before, was then made on the eastern umbra of the same spot (3), with results similar to those obtained for the western umbra. For the final exposure (4) the slit was kept on the eastern

[1] Right- and left-handed vortices have also been found in the same hemisphere.

umbra of the northern spot, and the Nicol rotated 90°. As was to be expected, the red components were brought into view, and the violet components extinguished. This spectrum is therefore precisely similar to that of the southern spot, which was taken with the Nicol in the reverse position.

This result has been confirmed by other photographs, which indicate that the direction of the displacement always depends upon the direction of the revolution in the vortex. If this relation is found by future observations to hold generally, we may conclude that the field is always produced by the revolution of particles carrying charges of like sign.

PLANE POLARIZATION ACROSS THE LINES OF FORCE

So far we have confined our attention to polarization phenomena observed along the lines of force. But it is well known that the doublets are, in general, transformed into triplets, when observed in a magnetic field at right angles to the lines of force. The components of the triplets are plane polarized, the central line in a plane at right angles to the plane of polarization of the side components. It should be possible to detect similar phenomena in spot spectra, if they are produced in a magnetic field.

It naturally happens that these spectra are most commonly observed when the spots are not very far removed from the center of the sun, because foreshortening near the limb reduces the umbra to a narrow strip difficult to keep on the slit. This may partially explain why our photographs of spot spectra, taken without polarization apparatus, show the doublets without a trace of a central component. But it does not account for the failure of the central line to appear in the spectra of spots well removed from the center. It is true that a few triplets occur in all of our spot spectra, such as λ 5781.97, λ 6064.85, and λ 6173.55. But these I have regarded as probable examples of an exceptional type of lines, observed in the laboratory as triplets along the lines of force. Mitchell records certain cases in which many spot doublets were seen as triplets,[1] but he also notes the existence of doublets in the spectra of spots near the limb.[2] In

[1] *Astrophysical Journal,* **24**, 80, 1906.

[2] *Ibid.,* **19**, 357, 1906.

PLATE XXIX

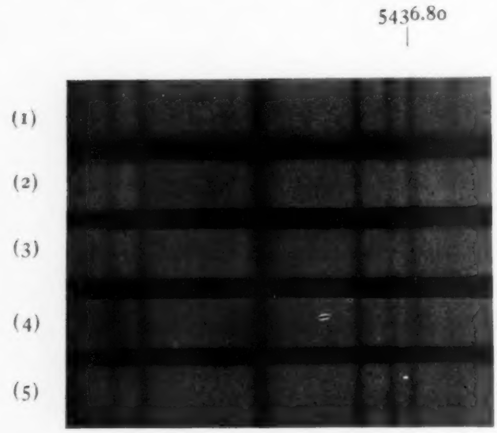


FIG. 1.—(1) and (5) Solar spectrum. (2) Spectrum of a spot near limb, Nicol 60° E. (3) Spectrum of a spot near limb, Nicol 60° W. (4) Spectrum of a spot near center, without rhomb or Nicol. Scale: 1 Ångström=6 mm.

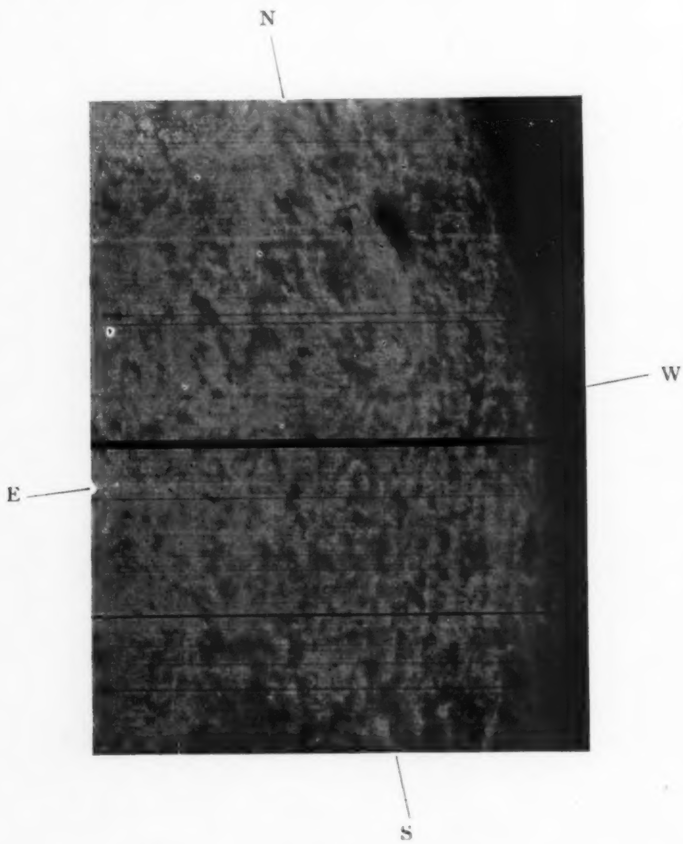


FIG. 2.—Spots near western limb, in which plane polarization of lines was observed.

1908, Sept. 14, $7^h\ 05^m$ A. M. Scale: Sun's Diameter=0.3 Meter.

one interesting observation described and illustrated by Mitchell, the lines appeared double across the umbra and one side of the penumbra, while on the other side of the penumbra they changed into triplets.[1] Since the beginning of my work on the Zeeman effect in the sun, there have been few opportunities to observe the spectra of spots near the limb. These I have utilized, not in attempting to photograph the triplets (which will be tried later), but in testing the polarization phenomena of the spot lines.

The rhomb was removed, and the Nicol employed alone. At right angles to the lines of force the Nicol, when in a certain position, should cut off the outer components of a triplet or the edges of a widened line. In another position, 90° distant, the central component should be extinguished, and the outer components or edges transmitted. Thus, in the second case, lines which are not too diffuse should be photographed as doublets, while in the first case the central component should appear alone.

Plate XXIX reproduces some photographs of a spot near the west limb, made on September 14. The seeing was poor, and neither the $H\alpha$ image nor the spectra are sharply defined. In Fig. 1, Plate XXIX, (1) and (5) represent the solar spectrum; (2) the spot spectrum, photographed with the Nicol set at 60° E.; (3) the spot spectrum, with Nicol set at 60° W.; (4) the same region of another spot spectrum, photographed near center of sun without Nicol. At 60° E. the Nicol cuts out the central line, while at 60° W. it transmits this line and cuts off the side components. Other settings of the Nicol gave the following results, which appear on the same negative (T 200): 90° E., single; 30° E., double; 0°, single, but wide; 30° W., single, but wide. Other photographs, made in this and other regions of the spectrum, gave similar results, the lines being narrow in some positions of the Nicol and wide in others. Only one case of undoubted doubling of the lines has been found. The short time available for work, under favorable atmospheric conditions, when a sufficiently large spot was near the limb, prevented the observations from being carried farther.

LABORATORY TESTS

If the widened lines and doublets in spot spectra are produced by a magnetic field, an equal degree of widening and an equal separation

[1] *Ibid.*, **24**, 80, 1906.

of the components of doublets should be found in the laboratory when the same lines are observed in a field of equal strength. As the necessary apparatus was fortunately available, the work was at once undertaken in our Pasadena laboratory by Dr. King. A brilliant spark is produced by a high potential transformer between electrodes supported in the field of a large Du Bois magnet. The light, passing through the pierced pole-pieces, falls on a lens, which forms an image of the spark on the slit of a vertical spectrograph, after reflection on a mirror mounted at an angle of 45° above the slit. This spectrograph, which is precisely similar to the 30-foot spectrograph used with the tower telescope, also stands in a constant temperature well, with the slit about three feet above the floor of the laboratory.[1] It may be used as an instrument of 30 feet focal length, or, as in the present case, a 5-inch (13 cm) objective of 13 feet (4 m) focal length, with a 5-inch plane grating, having 14,438 lines to the inch (567 to the mm), can be swung into the axis of collimation 13 feet below the slit. With this shorter focal length the dispersion in the second or third order of the grating is amply sufficient for the present purpose.

If all of the doublets observed in spot spectra could be photographed in the laboratory, it would be easy to make a satisfactory comparison. Unfortunately, however, most of these lines are very faint in the spark, and as the great majority of them occur in the less refrangible part of the spectrum, exposures of from fifteen to twenty hours are sometimes required to bring out even the stronger doublets. The results hitherto obtained for the iron doublets are brought together in the following table. I am indebted to Mr. Adams for

TABLE I

IRON DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda\text{, Spark}}{\Delta\lambda\text{, Spot}}$
6213.14	0.703	0.138	0.136	−0.002	5.2
6301.72	0.737	0.144	0.138	−0.006	5.3
6302.71	1.230	0.241	0.252	+0.011	4.9
6337.05	0.895	0.175	0.172	−0.003	5.2

[1] Hale, "The Pasadena Laboratory of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908.

these measures and for many of the others given in this paper. Miss Burwell and Miss Wickham have also assisted in the measurement of the spot and spark photographs.

The first column gives the wave-length of the doublet; the second, the separation in Ångströms of the components, observed along the lines of force in a field of about 15,000 gausses;[1] the third, the quantity given in column 2 divided by 5.1; the fourth, the separation of the components observed in the spot spectrum; the fifth, the residuals obtained by substracting the quantities in the third column from those in the fourth; the last column gives the ratio of the separation in the spark, for a field of about 15,000 gausses, to the observed separation in the spot. The mean value of this ratio, 5.1, gives an approximate measure of the strength of the field in spots, which comes out about 2900 gausses.

The agreement between the spot and laboratory results is so close that it can hardly be the result of chance. But when we come to the case of titanium, observed in the laboratory in a field of about 12,500 gausses, we find a very different condition of affairs.

TABLE II

TITANIUM DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda\text{, Spark}}{\Delta\lambda\text{, Spot}}$
5903.56	0.732	0.144	0.086	−0.058	8.5
5938.04	0.737	0.145	0.080	−0.065	9.2
6064.85	0.876	0.172	0.184	+0.012	4.8
6303.98	0.493	0.097	0.093	−0.004	5.3
6312.46	0.615	0.121	0.091	−0.030	6.8

If we use the factor 5.1 employed in the case of iron, we find that two of these doublets, λ 6064.85 and λ 6303.98, agree closely in spot and spark. In some of our spot photographs λ 6064.85 appears to be a triplet, though the components are not clearly separated. With the rhomb and Nicol a faint central component persists when either the red or the violet component is cut off. It is possible that this central line is due to some substance other than titanium in the spot, but it

[1] This value of the field strength may be in error by 1000 gausses, because of the disturbing effect of the iron electrodes.

is certainly very nearly in the position of the solar titanium line.[1] λ 6312.46 gives a residual of 0.03 Ångströms, which exceeds the error of measurement. The other doublets, λ 5903.56 and λ 5938.04, show in the spot spectrum but little more than one-half the separation that would be expected on the assumption that the strength of the field is the same for all of these lines.

On consideration it will be seen, however, that the separation of the doublets must depend, in some degree, on the distribution of the absorbing vapor in the solar atmosphere, and on the coefficient of absorption of the particular line employed. A striking instance of this kind, affecting lines of the same series, is illustrated in the case of hydrogen, described in a previous paper.[2] Although the $H\delta$ line extends to the upper part of the chromosphere and prominences, the mean level represented by its absorption is much lower than that given by $H\alpha$. The consequence is that $H\alpha$ enables us to photograph the solar vortices, the characteristic stream lines of which do not appear at the lower $H\delta$ level. Similarly, if the intensity of a given titanium line falls off rapidly, the level represented by this line may be comparatively low. If, on the other hand, its intensity curve is of such a form as to indicate that the absorption at higher elevations plays an important part, the mean level represented by the line may be considerably higher than in the previous case. To settle this question we must know: (1) The range of elevation in the spot of the vapors of iron, titanium, and other elements; (2) the intensities of the lines of these elements at different levels; (3) the rate at which the strength of the field decreases upward.

In the absence of information regarding the first two points, we may inquire as to the probable relative behavior of titanium, iron, and other elements if the distribution of the vapors at different levels were the same as in the chromosphere. From a discussion of a large number of photographs of the flash spectrum, made by different observers at several eclipses, Jewell has compiled a table showing the heights above the sun's limb attained by various lines in

[1] It is conceivable that under conditions analogous to those that give rise to the H_3 and K_3 lines, a doublet might be produced within the strong magnetic field of the spot, and a single line, at the center of the doublet, by the absorption of the vapor at a high level, where the field strength is low.

[2] *Solar Vortices*, p. 3.

the blue and violet.[1] The heights for titanium range from 100 miles (160 km) for λ 4466.0 to 3500 miles (5640 km) for λ 4466.7, while certain strong enhanced lines in the ultra-violet reach elevations of 6000 or 8000 miles (9660 or 12,880 km). For iron the minimum height is 200 miles (320 km) for λ 4482.4 and the maximum 1000 miles (1610 km) for λ 4584.0. Chromium ranges from 100 miles for λ 4280.2 to 1200 miles (1930 km) for λ 4275.0; manganese from "100 miles or more" for λ 4451.8 to "800 miles (1290 km) or more" for λ 4030.9; vanadium from 100 miles for λ 4390.1 to 200 miles for λ 4379.4. It thus appears that the range in level represented by the titanium lines is much greater than for the lines of iron, chromium, manganese, and vanadium. If the vapors were similarly distributed in spots, the maximum strength of field indicated by the titanium lines should therefore correspond with the maximum value for iron, but some titanium lines, produced by absorption at higher mean levels, should give lower field strengths. Chromium should agree more nearly with iron. Vanadium, if the less refrangible lines reach no greater elevations, should give closely accordant (maximum) values for the field strength. It will perhaps be possible, with the aid of the 30-foot spectrograph, to determine the relative levels in the chromosphere attained by most of the lines in question, but it is a much more difficult matter to do this for sun-spots. I hope, however, that our new spectroheliograph of 30-feet focal length may throw some light on this subject.

It is evident that these considerations will have no bearing on the present problem, unless the field strength decreases very rapidly upward in spots. That this probably occurs is shown by the fact that the D lines of sodium and the *b* lines of magnesium are usually but slightly affected in the spot spectrum,[2] and are displaced through a very small distance when the Nicol is rotated. Thus, at the level represented by these lines, which attain elevations in the chromosphere probably not exceeding 5000 miles, the field strength is reduced to a small fraction of its maximum value.

[1] "Total Solar Eclipses of May 28, 1900, and May 17, 1901," *Publications of the U. S. Naval Observatory*, Second Series, Vol. IV, Appendix I.

[2] Except for the strengthening of the wings, which may be produced by some cause other than a magnetic field.

The following doublets have been measured in the spectrum of chromium:

TABLE III

CHROMIUM DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda, \text{ Spark}}{4.9}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda, \text{ Spark}}{\Delta\lambda, \text{ Spot}}$
5304.36	0.636	0.130	0.188	+0.058	3.4
5387.16	0.676	0.138	0.085	−0.043	8.0
5713.00	0.610	0.124	0.161	+0.037	3.7
5781.40	0.755	0.154	0.121	−0.033	6.2
5781.97	0.922	0.188	0.212	+0.024	4.3
5783.29	0.772	0.158	0.137	−0.021	5.6
5784.08	0.720	0.147	0.121	−0.026	6.0
5785.19	0.707	0.144	0.137	−0.007	5.1

In photographing these lines in the spark, the strength of the field was 12,500 gausses. The strength of the field in spots, as indicated by the mean separation of the chromium doublets, is therefore 2600 gausses.

The above tables comprise all of the doublets hitherto observed both in spots and in our laboratory. It was at first hoped that the shifts of lines, on photographs of the spot spectrum made with the rhomb and Nicol, would serve as satisfactory data for comparison with laboratory results. But when the small magnitudes of these shifts, and the wide differences in the character of the lines were taken into account, it appeared that comparisons based on such data could have but little weight.

When a line is clearly resolved into a doublet, rotation of the Nicol cuts off the right-handed or left-handed light, and produces a shift equal to the separation of the components. But when the strength of the field is only sufficient to widen a line, that portion of the widened line where the right-handed and left-handed components overlap is composed of ordinary unpolarized light, not affected by rhomb or Nicol. If the components are narrow, this region may also be narrow. But if they are broad, only the outer edges of the components will be cut off when the Nicol is rotated.

If a magnetic field is the principal cause of the widening of lines in spots, their widths should be roughly proportional to the separation of the components of the corresponding doublets observed in a field

of equal strength. Bearing in mind the differences in the character of the lines, and the probable effect of variations in the mean level of absorption, we can hardly expect a very close agreement. But some evidences of relationship should appear, if a magnetic field is present. In the following tables the widths of various iron lines are compared with the separations of their components in the spark. To facilitate the comparison, the distances between the centers of the components, photographed in a field of about 15,000 gausses, are divided by 2.9, which reduces them to approximate equality with the widths in spots.

TABLE IV

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.9}$	Width in Spots	δ
6136.19	0.38	0.13	0.15	+0.02
6137.92	0.50	0.17	0.16	−0.01
6191.78	0.43	0.15	0.14	−0.01
6219.49	0.59	0.20	0.23	+0.03
6246.54	0.67	0.23	0.24	+0.01
6252.77	0.45	0.16	0.15	−0.01
6265.35	0.55	0.19	0.20	+0.01
6315.52	0.59	0.20	0.16	−0.04 Enhanced line
6318.24	0.40	0.14	0.14	0.00
6335.55	0.55	0.19	0.20	+0.01
6393.82	0.46	0.16	0.18	+0.02
6400.22	0.58	0.20	0.22	+0.02
6411.86	0.56	0.19	0.17	−0.02
6417.13	0.69	0.24	0.15	−0.09 Enhanced line
6420.17	0.57	0.20	0.19	−0.01
6421.57	0.64	0.22	0.18	−0.04
6431.07	0.54	0.19	0.19	0.00
6456.60	0.55	0.19	0.22	+0.03 Enhanced line
6495.21	0.54	0.19	0.18	−0.01

The exceptionally large residuals of the enhanced lines may be due to the fact that the weakening of these lines in spots makes them very difficult to measure. But it is perhaps possible that another cause may account for the negative sign of most of their residuals in Tables IV and VI. Assume that in the lower part of spots the field is most intense and the reduction of temperature most marked. In consequence of the reduced temperature, the enhanced lines are greatly weakened. Hence an unusually large proportion of the absorption which gives rise to these lines may occur at greater elevations, where

TABLE V
WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.9}$	Width in Spots	δ
5083.58	0.41	0.14	0.15	+0.01
5098.88	0.42	0.14	0.13	−0.01
5107.62	0.25	0.09	0.11	+0.02
5107.82	single*		0.14	
5110.57	0.45	0.15	0.17	+0.02
5123.90	single		0.09	
5125.30	0.41	0.14	0.09	−0.05
5127.53	0.51	0.18	0.15	−0.03
5137.56	0.45	0.15	0.13	−0.02
5139.43	0.56	0.19	0.16	−0.03
5139.64	0.51	0.18	0.15	−0.03
5143.11	0.42	0.14	0.11	−0.03
5162.45	0.47	0.16	0.14	−0.02
5167.68	0.35	0.12	0.12	0.00
5171.78	0.39	0.13	0.15	+0.02
5191.63	0.57	0.20	0.18	−0.02
5192.52	0.56	0.19	0.17	−0.02
5195.11	0.33	0.11	0.14	+0.03
5198.89	single		0.10	
5208.78	0.48	0.16	0.14	−0.02
5215.35	0.45	0.15	0.15	0.00
5216.44	0.23	0.08	0.12	+0.04
5217.55	0.47	0.16	0.15	−0.01
5227.04	0.47	0.16	0.19	+0.03
5227.36	0.32	0.11	0.15	+0.04
5230.03	0.50	0.17	0.15	−0.02
5233.12	0.38	0.13	0.14	+0.01
5242.66	0.29	0.10	0.11	+0.01
5250.82	0.49	0.17	0.14	−0.03
5263.49	0.47	0.16	0.13	−0.03
5266.74	0.38	0.13	0.14	+0.01
5269.72	0.39	0.13	0.15	+0.02
5273.56	0.53	0.18	0.11	−0.07
5276.17	0.31	0.11	0.12	+0.01
5281.97	0.44	0.15	0.11	−0.04
5283.80	0.49	0.17	0.14	−0.03
5302.48	0.48	0.17	0.17	0.00
5316.79	0.32	0.11	0.11	0.00 Enhanced line
5324.37	0.48	0.16	0.16	0.00
5328.24	0.37	0.13	0.17	+0.04
5328.70	0.49	0.17	0.13	−0.04
5340.12	0.48	0.16	0.16	0.00
5365.07	0.30	0.10	0.10	0.00
5367.67	0.31	0.11	0.12	+0.01
5370.17	0.36	0.12	0.12	0.00
5371.73	0.33	0.11	0.16	+0.05
5383.58	0.37	0.13	0.13	0.00
5393.38	0.52	0.18	0.18	0.00
5397.34	0.48	0.16	0.20	+0.04
5400.71	0.42	0.14	0.11	−0.03

* "Single" in these tables does not mean that the line is not affected by the field, but merely that it was not clearly separated on the plate measured. Several of these photographs were made in the first order.

TABLE V—*Continued*

Wave-Length	Δλ, Spark	Δλ, Spark / 2.9	Width in Spots	δ
5404.36	0.38	0.13	0.16	+0.03
5405.99	0.23	0.08	0.15	+0.07
5411.12	0.40	0.14	0.13	−0.01
5415.42	0.38	0.13	0.15	+0.02
5424.29	0.40	0.14	0.15	+0.01
5429.92	0.48	0.16	0.16	0.00
5434.74	single		0.11	
5447.13	0.51	0.18	0.19	+0.01
5455.83	single		0.20	

the temperature is higher and the field weaker. In this case, the field intensities indicated by the enhanced lines should be below the average value. In view of the fact that the rate of change of intensity with level is not the same for all lines, it is evident that many more cases must be included in any satisfactory test of this hypothesis. From the same course of reasoning it follows that lines which are most strengthened in spots should, in general, be most widened. This appears to be true, but a careful quantitative comparison will be made, both for strengthened and weakened lines, and published in a subsequent paper. It must not be forgotten that a considerable increase of temperature in the higher spot vapors would tend to produce true reversals. Discussion of this question must be reserved, however, until the spot spectra can be more thoroughly studied with this point in view.

In Table IV the mean residual, taken without regard to sign, is 0.021 Ångströms. If we omit the enhanced lines, because of their exceptional behavior in spots, the mean residual is reduced to 0.015 Ångströms. As the spot lines range in width from 0.14 to 0.24 Ångströms, the agreement is closer than would be expected to result from chance alone. When it is remembered that one or more secondary causes may also affect the width of the lines, the probability that a true relationship exists appears to be considerably increased.

A more refrangible region of the iron spectrum gives the results detailed in Table V.

Here the mean residual is 0.021 and the range in the width of the spot lines from 0.09 to 0.20 Ångströms. λ 5107.82, λ 5123.90, λ 5198.89, and λ 5434. 74, which are very narrow in spots, are not

quite separated on the laboratory plates. λ 5455.83, on the contrary, is single in the laboratory and fairly wide in spots. In this case, at least, there must be some cause of widening in spots other than a magnetic field.

A still more refrangible region of the iron spectrum gives the results contained in the following table:

TABLE VI

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.1}$	Width in Spots	δ
4427.48	0.32	0.15	0.16	+0.01
4433.39	0.28	0.13	0.12	−0.01
4442.51	0.35	0.17	0.18	+0.01
4443.36	0.10	0.05	0.12	+0.07
4454.55	0.26	0.12	0.10	−0.02
4459.30	0.32	0.15	0.12	−0.03
4461.82	0.32	0.15	0.14	−0.01
4466.73	0.26	0.12	0.15	+0.03
4469.54	0.32	0.15	0.12	−0.03
4484.39	0.29	0.14	0.12	−0.02
4494.74	0.25	0.12	0.14	+0.02
4522.80	0.20	0.10	0.08	−0.02 Enhanced line
4525.31	0.32	0.15	0.11	−0.04
4528.80	0.27	0.13	0.13	0.00
4531.33	0.29	0.14	0.12	−0.02
4548.02	0.22	0.10	0.10	0.00
4549.64	0.24	0.11	0.10	−0.01 Enhanced line
4556.06	0.27	0.13	0.12	−0.01 Enhanced line
4603.13	0.37	0.18	0.14	−0.04
	Mean 0.27		Mean 0.12	

It is interesting to note the progressive decrease toward the violet in the mean width of spot lines and the separation of the corresponding doublets in the spark, as shown by the following table. The means represent the three groups of lines given in Tables IV, V, and VI.

TABLE VII

Mean Wave-Length	Spot Lines Mean Width	Spark Doublets Mean Separation
6330	0.18	0.54
5267	0.14	0.42
4495	0.13	0.29

Although the rate of decrease is more rapid for the spark doublets than for the spot lines, it must be remembered that in the former case the mean separation of the components is given, while the mean width of the spot lines represents the separation of the components plus their width. The width of the components cannot be determined, except in the case of doublets, and therefore the rate of decrease falls off toward the violet, as the width of the spot lines approaches that of the solar lines. The extremely small average shift of the lines in the violet when the Nicol is rotated is in harmony with this view.

A group of twelve spot doublets near λ 4395, which belong to several different elements and have not yet been photographed in our laboratory, afford some additional evidence. The mean separations of groups of spot doublets in the red (Tables I, *Fe*, and II, *Ti*), green (Table III, *Cr*), and violet (those just mentioned) are given in the following table:

TABLE VIII

Mean Wave-Length	Spot Doublets	
	Number	Mean Separation
6186	9	0.137
5665	8	0.145
4395	12	0.085

Between λ 6186 and λ 5665 these doublets show no such progressive change as appears in Table VII.

Preston's law, $\frac{\Delta\lambda}{\lambda^2}=$const., has been found to hold rigorously only for the lines of certain series. It therefore could not be expected to apply with accuracy here, especially as the lines of different elements are included. Nevertheless it is of interest to determine whether the decrease in the separation of these doublets toward the violet proceeds at a similar rate. If we combine the separations for λ 6186 and λ 5665, we have 0.141 for the mean wave-length λ 5941. Then

$$\frac{0.141}{(5941)^2}=4.0\times10^{-9}$$

$$\frac{0.085}{(4395)^2}=4.4\times10^{-9}.$$

The iron doublets, whose mean separations for a field strength of about 15,000 gausses are given in Table VII, yield the following results.

$$\frac{0.44}{(5544)^2}=14.3\times10^{-9}$$

$$\frac{0.29}{(4495)^2}=14.3\times10^{-9}.$$

Thus the iron doublets follow the law very closely, while the approximate agreement with the spot doublets, though perhaps the result of chance, is not without interest.

Table IX gives the widths of various titanium lines in spots, and the separations of the components of the corresponding doublets, observed along the lines of force in a field of 12,500 gausses.

TABLE IX

WIDTHS OF TITANIUM LINES

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{3.4}$	Width in Spots	δ
5823.91	single		0.13	
5866.68	0.48	0.14	0.19	+0.05
5880.49	0.64	0.19	0.19	0.00
5899.52	0.50	0.15	0.18	+0.03
5903.56	0.73	0.21	0.19	−0.02
5918.77	0.73	0.21	0.20	−0.01
5922.33	single		0.12	
5938.04	0.74	0.22	0.17	−0.05
5953.39	0.52	0.15	0.13	−0.02
5966.06	0.47	0.14	0.16	+0.02
5978.77	0.38	0.11	0.14	+0.03
6064.85	0.88	0.26	0.27	+0.01
6085.47	0.81	0.24	0.20	−0.04
6091.40	0.65	0.19	0.15	−0.04
6092.74	0.55	0.16	0.16	0.00
6098.87	0.59	0.17	0.15	−0.02
6121.22	0.56	0.16	0.17	+0.01
6126.44	0.64	0.19	0.17	−0.02
6146.44	single		0.12	
6261.32	0.41	0.12	0.16	+0.04
6317.67	0.42	0.12	0.12	0.00
6336.33	0.56	0.16	0.15	−0.01
6366.56	0.55	0.16	0.18	+0.02

For titanium in this region the mean residual is 0.021 Ångströms for spot lines ranging in width from 0.12 to 0.27 Ångströms.

SIGN OF THE CHARGE THAT PRODUCES THE FIELD IN SUN-SPOTS

If the evidence presented in this paper renders probable the existence of a magnetic field in sun-spots, it is of interest to inquire concerning the sign of the charge which, according to our hypothesis, produces the field. In Lorentz's theory of the Zeeman effect in its simplest form, the motion of a single electron in a molecule of a luminous source is discussed.[1] This electron is supposed to be capable of displacement in all directions from its position of equilibrium, toward which it is drawn by an elastic force, which is proportional to the displacement but independent of its direction. Let e be the charge of the particle, m its mass, fr the elastic force caused by a displacement r, f being a positive constant. The frequency of the vibrations, whether they be linear, elliptical, or circular, will be

$$n_0 = \sqrt{\frac{f}{m}}.$$

We may now suppose the light-source to be placed in a homogeneous magnetic field of intensity H. A particle carrying a charge e, and moving with velocity v, will be subjected to a force perpendicular to the field and to the direction of motion of the particle, the magnitude of which may be represented by $ev\mathrm{H} \sin (v, \mathrm{H})$. It is evident that the electron may have three different motions, each with its own frequency. Linear vibrations parallel to the lines of force, having the frequency n_0, will not be affected by the magnetic field. Circular vibrations in a plane perpendicular to the lines of force will be affected differently, depending upon whether they are right-handed or left-handed. If r is the radius of a circular orbit and n the frequency, the velocity of the electron will be $v = nr$ and the centripetal force will have the value mn^2r. We may now consider the effect on the motion of the electron of the elastic force fr and of an electromagnetic force

$$ev\mathrm{H} = enr\mathrm{H}.$$

For a positive charge the latter force is directed toward the center if the motion is clockwise, as seen by an observer toward whom the lines of force are directed. We then have

$$mn^2r = fr + enr\mathrm{H}.$$

[1] The following outline of the theory is taken from Lorentz's "Theorie des phénomènes magnéto-optiques récemment découverts," *Rapports*, Congrès international de physique, **3**, 1, 1900.

This frequency n differs very slightly from the frequency n_0; thus the last term of the equation must be much smaller than the term fr, so that we may write

$$n=n_0+\frac{eH}{2m}. \tag{1}$$

This expression gives the frequency of the right-handed (clockwise) vibrations. For the left-handed vibrations we have

$$n=n_0-\frac{eH}{2m}. \tag{2}$$

As seen along the lines of force a single line in the spectrum is thus transformed into a doublet, the components of which are circularly polarized. An observer toward whom the lines of force are directed will find that the light of the component of greater wave-length, whose frequency has been decreased by the field, is circularly polarized in the right-handed or clockwise direction. Hence (2) is greater than (1), and it follows that the charge e of the electron which produces the spectral lines must be negative.

In the case of the solar vortices we have to consider two sets of charged particles, which may be entirely distinct from one another: (1) those whose vibrations give rise to the lines in the spectra of spots, and (2) those that carry the charge which, by the hypothesis, produces the magnetic field. The Zeeman effect supplies the means of determining the direction of the lines of force of the sun-spot fields, and photographs of the vortices, made with the spectroheliograph, indicate the direction of their rotation. Thus we are in a position to determine the sign of the charge carried by the particles which produce the fields. As pointed out independently by König and Cornu, the violet component of a magnetic doublet observed along the lines of force is formed by circular vibrations, having the direction of the current flowing through the coils of the magnet.[1] From observations of circularly polarized light, made in our Mount Wilson laboratory by Dr. St. John and confirmed by myself, it appears that when the Nicol prism of the tower spectrograph stands at 60° E. it transmits the violet component of a doublet produced in a magnetic field directed toward the observer. From Biot and Savart's law the direction of

[1] See Cotton, *Le phénomène de Zeeman*, chap. vii; König, *Wied. Ann.*, **62**, 240, 1897.

the current causing such a field is counter-clockwise, as seen by the observer. In the same position the Nicol also transmits the violet component of a doublet produced in a sun-spot surrounded by a vortex rotating clockwise. As a negative charge rotating clockwise produces a field of the same polarity as an electric current flowing counter-clockwise, we may conclude that the magnetic field in spots is caused by the motion of negative ions or electrons.

PROBABLE SOURCE OF THE NEGATIVE CORPUSCLES

We may now consider the probable source of a sufficient number of negative corpuscles to produce a field of about 2900 gausses in sun-spots.

In his *Conduction of Electricity through Gases*, p. 164, J. J. Thomson writes as follows:

> We thus are led to the conclusion that from an incandescent metal or glowing piece of carbon "corpuscles" are projected, and though we have as yet no exact measurements for carbon, the rate of emission must, by comparison with the known much smaller rate for platinum, amount in the case of a carbon filament at its highest point of incandescence to a current equal to several amperes per square centimeter of surface. This fact may have an important application to some cosmical phenomena, since, according to the generally received opinion, the photosphere of the sun contains large quantities of glowing carbon; this carbon will emit corpuscles unless the sun by the loss of its corpuscles at an earlier stage has acquired such a large charge of positive electricity that the attraction of this is sufficient to prevent the negatively electrified particles from getting right away from the sun; yet even in this case, if the temperature were from any cause to rise above its average value, corpuscles would stream away from the sun into the surrounding space.

On another page (168) Thomson also remarks: "The emission of the negative corpuscles from heated substances is not, I think, confined to the solid state, but is a property of the atom in whatever state of physical aggregation it may occur, including the gaseous." After illustrating this in the case of sodium vapor, Thomson adds (p. 168):

> The emission of the negatively electrified corpuscles from sodium atoms is conspicuous as it occurs at an exceptionally low temperature; that this emission occurs in other cases although at very much higher temperatures is, I think, shown by the conductivity of very hot gases (or at any rate by that part of it which is not due to ionization occurring at the surface of glowing metals), and especially by the very high velocity possessed by the negative ions in the case

of these gases; the emission of negatively electrified corpuscles from atoms at a very high temperature is thus a property of a very large number of elements, possibly of all.

Thus the chromosphere, as well as the photosphere, may be regarded as copious sources of negatively electrified corpuscles. The part played by these corpuscles in the sun-spots cannot be advantageously discussed until the nature of the vortices is better understood.[1] At present it is enough to recognize that the supply of negative electricity appears amply sufficient to account for the magnetic fields.

Let n be the number of corpuscles per unit cross-section passing a given point in unit time and e the charge on each corpuscle. Then we have, for the current carried by the corpuscles, $c=ne$. H. A. Wilson found that in a vacuum tube, at pressures up to 8.5 mm, the current at the cathode was 0.4 p milliamperes per sq. cm, where p is the pressure in millimeters.[2] If $p=8.5$, we have $c=3.4\times 10^{-3}$ amperes. Assume the velocity of the corpuscles in this case to be of the order of 10^4 km per sec. In a solar vortex (if the charged particles are carried with it) the velocity may be taken as of the order of 100 km per sec.[3] Then if the number of corpuscles per sq. cm were the same in the two cases, the current in the sun would be of the order of 3.4×10^{-5} amperes per sq. cm at the same pressure.

We m y now assume the corpuscles to be moving at a velocity of 100 km per second in an annulus 25,000 km wide, 1000 km deep, and 100,000 km in diameter surrounding a sun-spot. Taking the current strength to be as above, 3.4×10^{-5} amperes per sq. cm, the intensity of the resulting magnetic field comes out 1000 gausses.

Such a calculation is of little value, except for the purpose of indicating that a magnetic field of the observed order of magnitude might conceivably be produced on the sun.[4]

EXTERNAL FIELD OF SUN-SPOTS

We have already seen that the strength of the field in spots apparently changes very rapidly along a solar radius, and is small at the upper level of the chromosphere.

[1] For this reason a discussion of the very interesting suggestion of Professor E. F. Nichols, that the positively and negatively charged particles are separated by centrifugal action in the spot vortex, is reserved for a subsequent paper.

[2] *Philosophical Magazine* (6), **4**, 613, 1902.

[3] *Solar Vortices*, p. 13.

[4] See a similar calculation by Zeeman in *Nature* for August 20, 1908.

If subsequent work proves this to be the case, it will appear very improbable (as indicated by theory) that terrestrial magnetic storms are caused by the direct effect of the magnetic fields in sun-spots. Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots.

CONCLUSION

Although the combined evidence presented in this paper seems to indicate the probable existence of a magnetic field in sun-spots, the weak points of the argument should be clearly recognized. Among these are the following:

1. The failure of our photographs to show the central line of spot triplets before the spots are very close to the limb.

2. The presence in the spot spectrum of at least one triplet, which appears as a doublet when observed along the lines of force in the laboratory.

3. The absence of evidence to support the hypothesis that the imperfect agreement between spot and laboratory results is due to differences in the mean level of absorption.

4. The apparent constancy of the field strength, as indicated by the nearly uniform width of the doublets in different spots.

5. The difficulty of explaining, on the basis of our present fragmentary knowledge of solar vortices, the observed strength of field in the umbra and penumbra, and especially its variation with level.

As the resolving power of the 30-foot spectrograph is sufficient to resolve completely only the wider spot doublets, the central line could not be separately distinguished in other cases, even if it were present. Hitherto it has been possible to photograph the spectra of only the largest spots, because the images of other spots, as given by the tower telescope, are too small. The need of a telescope giving a much larger image of the sun, and a spectrograph of greater resolving power and focal length, which has been felt in previous work, is strongly emphasized by this investigation. Such apparatus would also permit the spectrum of the chromosphere, and many other solar phenomena, to be studied to great advantage.

As regards the nature of the vortices, the principal question is whether the gyratory motion primarily concerned in the production

of the magnetic field is outside the boundaries of the spot or within the umbra. In the former case we must face various difficulties, such as the apparent constancy of the field in different spots, and the fact that its intensity rapidly decreases upward. If a spot vortex may be considered analogous to an anti-cyclone, and the assumption be made that the gyratory motion of the low-level vapors produces the field, these difficulties may be lessened. The view that the field is produced by the gyratory motion of vapors within the umbra raises other difficulties which may also be serious. Fortunately there is reason to hope that observations now in progress may throw light on several of these questions.

Mount Wilson Solar Observatory
October 7, 1908

ADDENDUM

The fact that the doublets in the sun-spot spectrum do not change to triplets, even when the spot is as much as 60° from the center of the sun, appeared, when the proof of the above paper was corrected, to be a serious argument against the magnetic field hypothesis. Thanks to the recent work of Dr. King, this difficulty no longer exists, at least in the case of several iron and titanium lines. Photographs of the spark spectrum in a strong magnetic field, taken at right angles to the lines of force, show that the iron lines $\lambda\lambda$ 6213.14, 6301.72, and 6337.05 are doublets, with no trace of a central component. As these lines are also doublets when observed parallel to the lines of force, it is only natural that they should be double in spots, wherever situated on the solar disk. λ 6173.55, which is a fine triplet in spots, is a triplet when observed at right angles to the lines of force. But the line λ 6302.71 is the most interesting of all. In Table I this is classed as a spot doublet. In the spot spectrum the line appears as a triplet, but so decidedly asymmetrical that I supposed the intermediate line to be due to some element other than iron, greatly strengthened in the spot. It now turns out, however, that this is an asymmetrical triplet in the spark, when observed at right angles to the lines of force. Moreover, the displacement of the intermediate line from the center is toward the red, both in the spot and in the spark. As soon as a suitable photograph can be taken

in a higher order of the grating, it will be possible to measure the asymmetry in the spark, as has already been done in the spot spectrum.

The titanium lines $\lambda\lambda$ 6303.98 and 6312.46, which are double in spots, are also double in the spark, when observed at right angles to the lines of force. λ 6064.85, already mentioned as a triplet in spots, with a rather faint central component, is a triplet, with strong central component, in the spark under the above conditions.

The titanium spot doublets $\lambda\lambda$ 5903.56 and 5938.04 (Table II) have not yet been observed at right angles to the lines of force.

These results leave no doubt in my mind that the doublets and triplets in the sun-spot spectrum are actually due to a magnetic field. As I am now designing a spectrograph of 75 feet (23 m) focal length, for use with a tower telescope of 150 feet (46 m) focal length, I hope it may become possible to investigate small spots, as well as large ones, and to resolve many of the close doublets and triplets in their spectra.

NOVEMBER 4, 1908

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